

# **Nevada Water Resources Research Institute Annual Technical Report FY 2013**

# Introduction

Success and dedication to quality research has established the Division of Hydrologic Sciences as the recognized "Institute" under the Water Resources Research Act of 1984 (as amended). A total of 54 Institutes are located at colleges and universities in the 50 states, the District of Columbia, Puerto Rico, and the U.S. Virgin Islands.

The primary mission of the Nevada Water Resources Research Institute is to inform the scientists of Nevada.

## Research Program Introduction

Nevada is the most arid state in the United States and, like much of the semi-arid southwest, is experiencing significant population growth and possible future climate change. Defining available water resources more accurately and using these resources more efficiently, begins to frame the important issues surrounding water supply. However, water supply issues are growing increasingly complex due to competing demands in support of agricultural, domestic/industrial, and environmental functions. This increased complexity and associated likelihood of potential conflict heightens the need for the development and dissemination of sound science to support informed decision-making.

Beyond water quantity, issues concerning water quality are increasingly of concern. Groundwater supports the population in rural areas of Nevada, with a water quality that is often reflective of the natural abundance of geothermal resources (e.g. above average levels of certain elements and minerals). The development and enforcement of new drinking water quality standards could have significant economic consequences to such rural communities. Therefore, it is important to establish sound supporting science to drive future regulatory and implementation strategies. The increased importance of defining and understanding surface water quality, as demonstrated through the TMDL (Total Maximum Daily Load) analysis process, is placing new demands on our ability to adequately monitor and model the often highly dynamic nature of our flowing waters. Again, sound supporting science is needed to establish and achieve appropriate in-stream water quality targets.

## Measuring Water Use of Tamarisk and Impacts from Biocontrol: Lower Virgin River, NV

### Basic Information

<b>Title:</b>	Measuring Water Use of Tamarisk and Impacts from Biocontrol: Lower Virgin River, NV
<b>Project Number:</b>	2011NV178B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	2/28/2014
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV03
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Acid Deposition, Ecology, Water Quantity
<b>Descriptors:</b>	Tamarisk, Virgin River, Water
<b>Principal Investigators:</b>	Kumud Acharya

### Publications

1. Conrad, B., Acharya, K., Dudley, T., and Bean, D. (2013) Episodic herbivory by the tamarisk beetle in *Tamarix ramosissima* increases leaf litter nitrogen and stem starch content: a short communication. *Journal of Arid Environments* 94, 76-79.
2. Sueki, S., Acharya, K., Healey, J., and Jasoni, R. (2013) Defoliation effect of *Diorhabda carinulata* on evapotranspiration from *Tamarix* in the Lower Virgin River: Are Beetles Saving Water? 2013 Universities Council on Water Resources / National Institutes for Water Resources Annual Conference, Lake Tahoe, CA. June 11 to 13, 2013.
3. Sueki, S., J. Healey, K. Acharya, J. Huntington. 2013. The Virgin River tamarisk defoliation by *Diorhabda carinulata*: Its effects on evapotranspiration rates and groundwater consumption. 2013 AGU Fall Meeting, San Francisco, CA. Dec. 9-13, 2013.

## NIWR Project 2011NV178B

### Measuring Water Use of Tamarisk and Impacts from Biocontrol: Lower Virgin River, NV

#### Problem and Research Objectives

The lower Virgin River is a tributary of the Colorado River System and considered a major component of the water budget of the Southwest. The Virgin River flows through the Tri-State area of Arizona, Utah, and Nevada with a mean flow rate of 100 cubic feet per second. The State of Nevada contains 53% of the drainage basin followed by equal shares to Arizona and Utah at 24%. The river's relevance to each state is an important issue as rising population growth results in greater demands on a depleting, limited water supply. To compound the situation, an avaricious water-consuming plant has inundated this region reducing water availability. The invasion of non-native plant species, *Tamarix* (tamarisk, salt cedar), along the lower Virgin River and other river systems has developed riparian communities of mono-specific thickets. In addition to detrimental effects on biodiversity along these corridors, tamarisk commonly occurs in dense thickets that result in high evapotranspiration (ET) rates commonly emanating from relatively shallow groundwater. Extraction of groundwater can reduce stream flow, increase the salinity of soils and vadose zones, thus potentially degrading water quality for irrigation and other potable uses. Traditional eradication efforts such as herbicidal treatment, fire and mechanical removal have either proven too costly or have negative impacts on the native flora which they are intending to restore. Recently, new eradication efforts have shifted towards the use of a biocontrol agent, the saltcedar leaf beetle (*Diorhabda carinulata*). The beetle was introduced to reduce tamarisk leaf cover along many western watersheds. Defoliation of tamarisk in lieu of *Diorhabda carinulata* infestation has been occurring along the Colorado River and its tributaries since the release of the beetle in 2001. Recently, the establishment of large beetle populations in Lower Virgin River have been evident and known to extend south into the Overton arm region of the Lake Mead in 2011. The rapid progression of these beetles down the Colorado River basin provides a unique opportunity to directly assess the beetle's defoliation of tamarisk as a water savings measure. These savings can be accessed by measuring the change in ET while the beetles are actively migrating through tamarisk groves. The primary goal of the research was to quantify ET prior to and following episodic herbivory by the leaf beetle, calculate the difference between ET of those times and estimate to a net water savings of along the Virgin River. Additionally impacts of beetles' defoliation on tamarisk physiology and ecology were also studied by measuring leaf litter nitrogen (N), stem starch contents and pre- and post-defoliation temperatures in a tamarisk stand.

## Methodology

The study focused primarily on a research site established by funding from the U.S. Bureau of Reclamation (Technical Services Center, Denver) along the alluvial-filled valley of the lower Virgin River and other supplemental field data. The site consisted of a groundwater monitoring well and the equipment necessary to utilize the classic Eddy Covariance technique to determine atmospheric fluxes and to obtain accurate estimates of ET. Eddy Covariance set-up includes: 1) a 3D sonic anemometer (model CSAT3) mounted one meter above the canopy, 2) an open-path infrared gas analyzer (model CS7500) mounted one meter above the canopy, 3) a REBS net radiometer (model Q7.1), 4) two soil heat flux plates (model HFP01SC), 5) two soil thermocouple probes (model TCAV-L), 6) two soil water reflectometers (model CS616), and 7) air temperature/relative humidity probe (model HMP45C-L).

Data was stored on a datalogger (Campbell Scientific CR5000) equipped with a 2 Gb memory card. Data was collected monthly during site visits where “swapping” the full memory card with an empty one occurred. Additionally, real-time data was checked with a lap-top PC to ensure appropriate sensor operation. Fluxes were later calculated off-line and corrected using EddyPro (LI-COR Inc.). This technique was used on all data and allowed for the following corrections: 1) despiking and low pass filtering, 2) sonic temperature path correction, 3) sonic flow distortion, 4) rotating velocity signals, 5) sonic temperature density correction, 6) highpass filtering signals, 7) frequency response corrections, 8) sonic temperature correction and 9) density corrections. All corrections were made to the 10-Hz time series data (time interval of 0.1 second) prior to calculating 30-minute averages. Fluxes were then calculated using the averaged data. The groundwater monitoring well was used to record diurnal groundwater fluctuations on 30-minute averages and utilizes a pressure transducer installed in a shallow piezometer (5.08 cm diameter). Data from the transducer was downloaded to a computer during each site visit.

Physiological effect of beetles’ defoliation was studied by collecting stem and foliage at five sites representing a chronosequence in years since initial beetle establishment and defoliation (Table 1). Stem and foliage collections occurred in early January of 2011, when Tamarix plants were inactive during their deciduous winter phase. Litter samples from all locations except Dolores (samples were not available at the time of analysis due to a delay in sampling at that site) were analyzed for N using a Perkin Elmer CHN analyzer (Perkin Elmer Inc., San Jose, CA, USA). Finely ground stem samples from all sites were analyzed for starch content using the enzymatic method.

Temperature loggers, iButtons, mainly to monitor temperature changes in response to herbivory were placed in a monoculture of mature tamarisk stand on the upstream of the

Riverside Road Bridge Virgin River, Mesquite. iButtons were also placed on tamarisks outside of tamarisk stand as controls.

Table 1. Site location and herbivory classification for stem and leaf litter collection.

Site	Classification	Location	Herbivory Histroy
Meadowland's farm	Control	36°41'54.23"N, 114°15'27.46"W	No defoliation
Riverside Bridge	Low	36°44'00.23"N, 114°13'08.12"W	1 <sup>st</sup> defoliation end of 2010
Big Bend	Low	36°50'20.63"N, 113°59'11.35"W	1 <sup>st</sup> defoliation 2010
School Bus	Intermediate	36°54'36.16"N, 113°53'45.36"W	1 <sup>st</sup> defoliation 2009
St. George River Rd. UT	High	37°05'12.44"N, 113°33'21.59"W	3+ yrs of defoliation
Dolores River, UT	High	38°44'37.76"N, 109°07'55.48"W	4+ yrs of defoliation

### Principle Findings and Significance

Water use of tamarisk and impacts from biocontrol agent, leaf beetles were studied. The results showed:

- Beetle herbivory decreased tamarisk ET along with magnitude of diurnal groundwater fluctuations (Figures 1 and 2).
- The defoliation effects were short lived as tamarisk quickly recovered and established new growth.
- Magnitude of the effects of defoliation seemed to be dependent upon the growth stage of tamarisk at the time of defoliation. One time defoliation of 2011 reduced more tamarisk ET compared to the ET reduction caused by two defoliation events of 2012.
- The differences in pre- and post-defoliation total ET from April to November showed 0.16 m in 2011 and 0.08m in 2012, approximately 17% and 8% reductions, respectively (Figure 3).
- Temperature and precipitation in the eddy covariance field site did not show noticeable differences throughout three years of observation period (Figure 4). In general, precipitation was low and temperature was high in summer. The temperature and precipitation data also supported that the reduction of ET and the magnitude of groundwater fluctuations in 2011 and 2012 was caused by beetles herbivory.

- Plants that had not experienced herbivory by the beetle displayed significantly lower quantities of both litter nitrogen and stem starch than beetle-affected tamarisk trees (Table 2).
- Higher levels of nitrogen in leaf litter from beetle-affected trees may be a result of herbivory-induced desiccation and foliar mortality prior to the translocation of nitrogen back into plant reserves.
- Higher stem starch may be a result of either phloem damage reducing the translocation of photoassimilates, or an increase in the shunting of carbohydrates to the site of new leaf growth.
- There were no significant differences in both litter nitrogen and stem starch among beetle-affected sites representing a chronosequence of defoliation history. The lack of correlation between years of herbivory and both leaf litter nitrogen and stem starch may indicate that as of yet there have not been sufficient defoliation events to yield anticipated host plant impact.
- There was hardly any noticeable difference between the pre-defoliation and post-defoliation temperatures (Figure 5) inside tamarisk canopy.
- In general, temperatures inside the canopy were cooler than outside.
- The difference between inside and outside of the canopy at 2m height was more pronounced in the morning and evening than midday while the difference on the ground temperature was the highest during afternoon.
- In contrast, ground temperatures were higher inside canopy compared to bare ground (control) during months of November and December. This is probably due to wind effect outside of canopy. Heat is more easily diffused from the ground to the air when there is no tamarisk leading to cooler ground temperature.



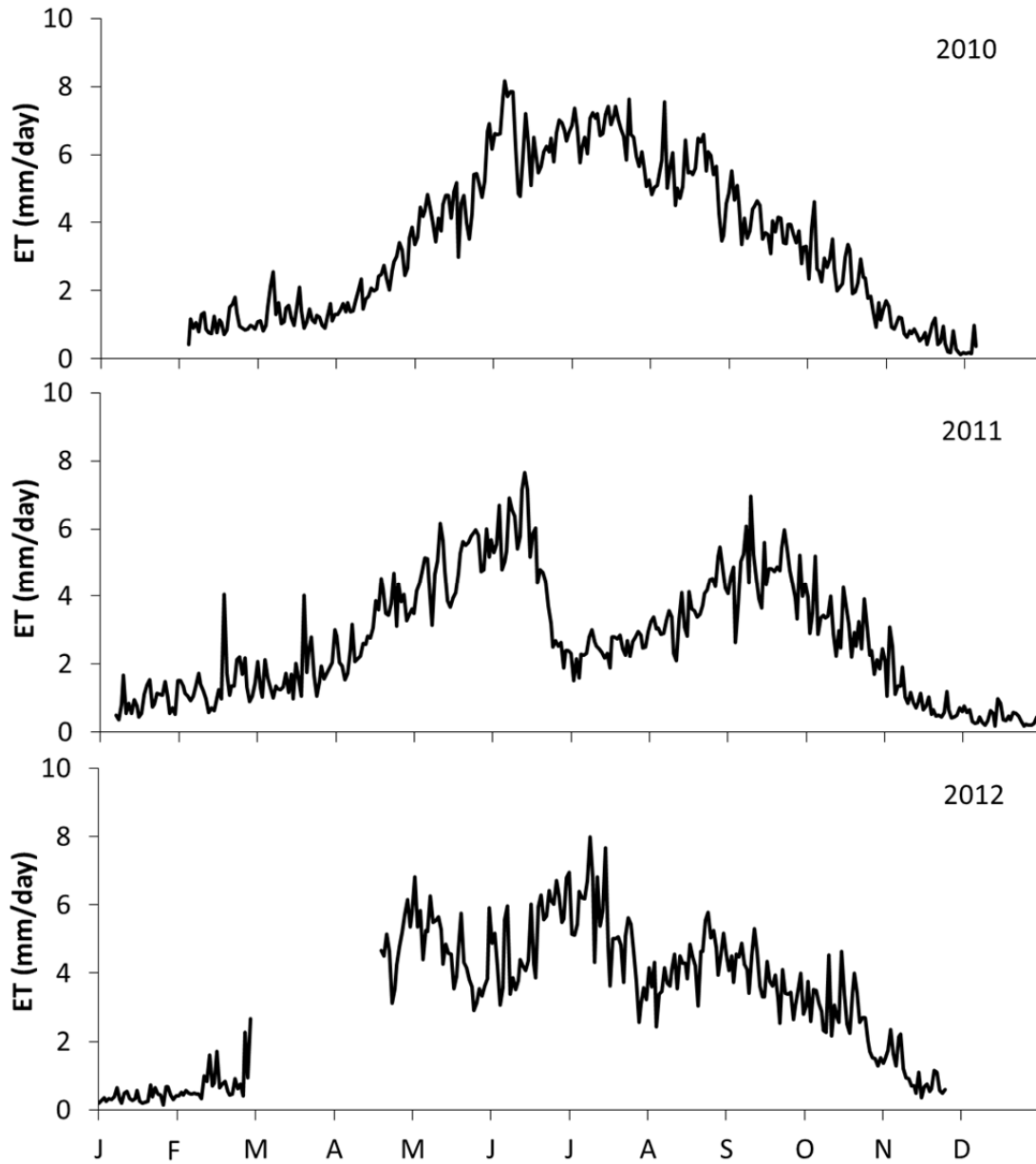


Figure 1. Daily tamarisk evapotranspiration measured at the eddy covariance site along the Lower Virgin River near Mesquite, NV in 2010, 2011 and 2012. Beetles arrived at the field site in the late summer of 2010 and defoliated tamarisks in 2011 and 2012.

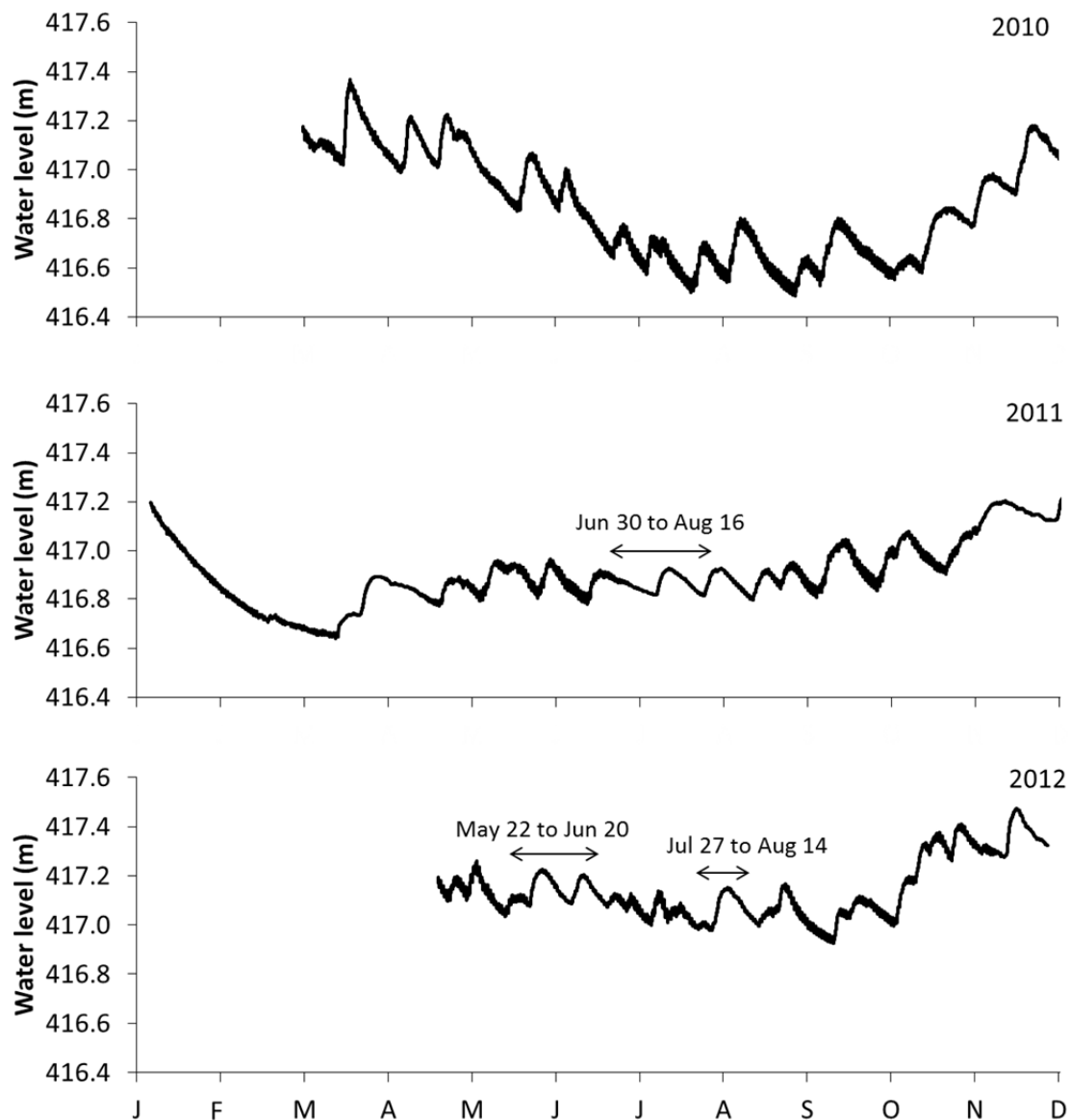


Figure 2. Groundwater level measured at 30-minutes intervals in 2010, 2011 and 2012 measured at the eddy covariance field site along the Lower Virgin River near Mesquite, NV. Dated period in the figure showed reduction of the magnitude of diurnal fluctuations. Beetles arrived at the field site in the late summer of 2010 and defoliated tamarisks in 2011 and 2012.

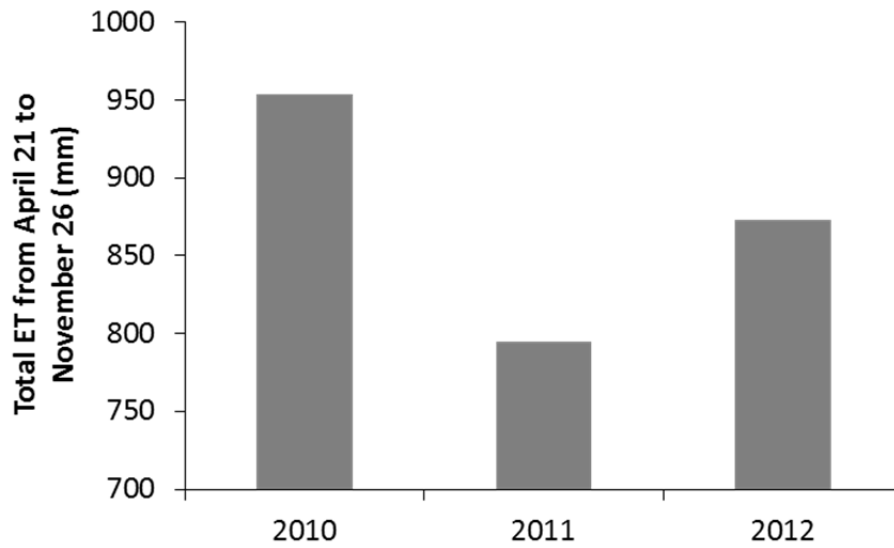


Figure 3. Total evapotranspiration from April 21 to November 26 in 2010, 2011 and 2012 measured at the eddy covariance field site along the Lower Virgin River near Mesquite, NV. Beetles arrived at the field site in the late summer of 2010 and defoliated tamarisks in 2011 and 2012.

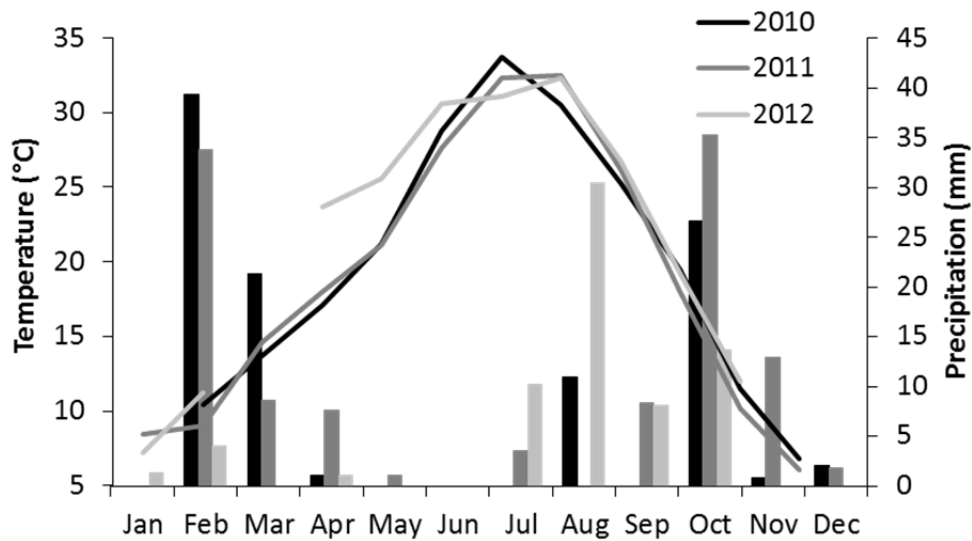


Figure 4. Monthly average temperature and monthly precipitation measured at the eddy covariance field site along the Lower Virgin River near Mesquite, NV in 2010, 2011 and 2012.

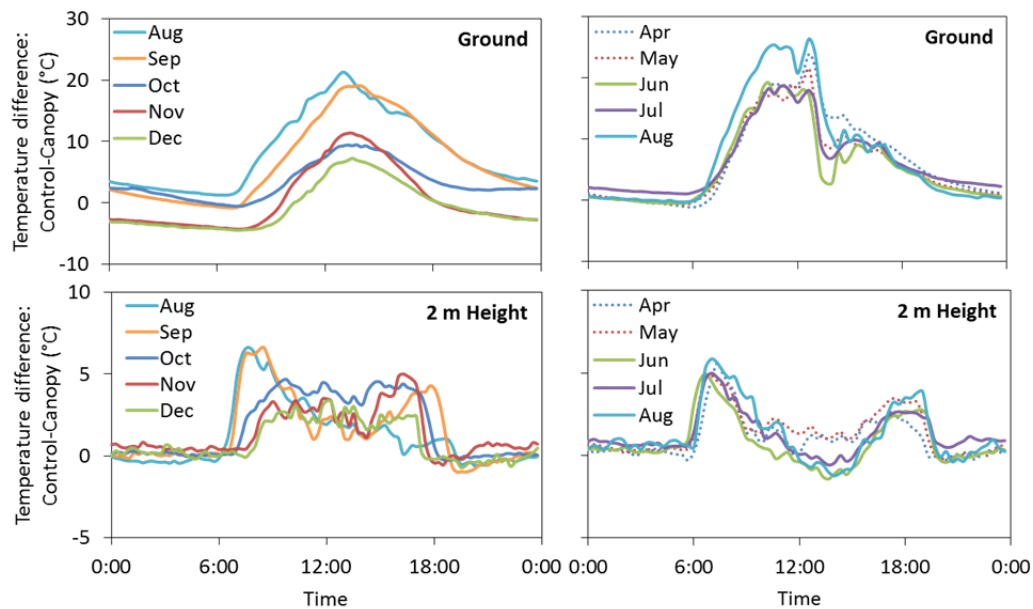


Figure 5. Differences between temperatures measured outside (control) and inside the tamarisk canopy on the upstream of the Riverside Road Bridge Virgin River, Mesquite. Left and right figures are the results from 2010 and 2011, respectively. Beetles arrived at the field site in the late summer of 2010 and defoliated tamarisks in 2011.

Table 2. Leaf litter nitrogen and stem starch content in control and beetle-affected sites

Site	N leaf litter %		Stem starch (mg/ml)	
Control	$0.85 \pm 0.05$		$40.8 \pm 6.7$	
Riverside	$1.78 \pm 0.08$	*	$64.8 \pm 3.7$	*
Big Bend	$2.00 \pm 0.16$	*	$67.0 \pm 7.0$	*
School Bus	$1.63 \pm 0.15$	*	$64.3 \pm 4.4$	**
St. George	$1.63 \pm 0.08$	*	$68.5 \pm 5.3$	**
Dolores	X		$69.8 \pm 4.0$	**

Note: Asterisks indicate ANOVA;  $p < 0.05^*$  and  $p < 0.01^{**}$

### Information Transfer Activities

#### Papers:

- Conrad, B., Acharya, K., Dudley, T., and Bean, D. (2013) Episodic herbivory by the tamarisk beetle in *Tamarix ramosissima* increases leaf litter nitrogen and stem starch content: a short communication. *Journal of Arid Environments* 94, 76-79.
- Sueki, S., K. Acharya, J. Huntington, R. Liebert, J. Healey, R. Jasoni, M. Young. Defoliation effect of tamarisk biocontrol agent, *Diorhabda carinulata*, on evapotranspiration and groundwater level. In review.
- Liebert, R., J. Huntington, C. Morton, S. Sueki, K. Acharya. Estimating water salvage from leaf beetle induced tamarisk defoliation in the Lower Virgin River using satellite based energy balance. In review.
- Conrad, B., K. Acharya, T. Dudley, D. Bean. 2013. Episodic herbivory by the tamarisk beetle in *Tamarix ramosissima* increases leaf litter nitrogen and stem starch content: a short communication. *Journal of Arid Environments* 94, 76-79.

#### Presentations:

- Sueki, S., J. Healey, K. Acharya, J. Huntington. 2013. The Virgin River tamarisk defoliation by *Diorhabda carinulata*: Its effects on evapotranspiration rates and groundwater consumption. 2013 AGU Fall Meeting, San Francisco, CA. Dec. 9-13, 2013.
- Sueki, S., K. Acharya, J. Healey, R. Jasoni. 2013. Defoliation effect of *Diorhabda carinulata* on evapotranspiration from *Tamarix* in the Lower Virgin River: Are Beetles Saving Water? 2013 Universities Council on Water Resources / National Institutes for Water Resources Annual Conference, Lake Tahoe, CA. Jun. 11-13, 2013.

### Student/other Support

The project provided partial support to a postdoctoral researcher (Sachiko Sueki) for data analysis and an Assistant Research Scientist (John Healey) for field data collection. The project partially supported a graduate student, Mahesh Bhattarai who graduated in spring, 2013.

# Effects of Regional Climate Change on Snowpack in Northern Nevada: Research and Education

## Basic Information

<b>Title:</b>	Effects of Regional Climate Change on Snowpack in Northern Nevada: Research and Education
<b>Project Number:</b>	2011NV180B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	2/28/2014
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV02
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Climatological Processes, Hydrology, Water Supply
<b>Descriptors:</b>	Snowpack, Climate Change
<b>Principal Investigators:</b>	Rina Schumer, Anna Knust

## Publication

1. Backes, T. M.; Schumer, R. A.; Mejia, J. F.; Kaplan, M. L.; Redmond, K. T., (2013) Combined effect of mid-level jets and atmospheric rivers on winter precipitation in the eastern Sierra Nevada. American Geophysical Union Fall Meeting. San Francisco, CA.

**NIWR Project 2011NV180B**  
**Effects of Regional Climate Change on Snowpack in Northern Nevada:**  
**Research and Education**

## **Problem and Research Objectives**

Hal Klieforth, a former Desert Research Institute meteorologist, began measuring monthly precipitation and snow water equivalent at 29 sites between Spooner Summit and Henness Pass Junction (Figure 1) in the mid 1960s. Until recently, the majority of these data only existed as hard copies located in Mr. Klieforth's personal office in Bishop, CA. This dataset is unique in its temporal and spatial resolution; measurements were recorded after nearly every storm at sites spanning elevations of 1,400 to 2,590 masl over approximately 24 linear kilometers. The goals of this project are to 1) complete digitization and QA/QC of the Klieforth data set and 2) analyze the spatio-temporal statistics of precipitation and SWE from the newly compiled dataset combined with observations recorded by other sources (e.g. Snotel and USGS stream gage sites).

## **Methods**

Digitization and QA/QC of this dataset is labor intensive and requires consultation with data collectors. Statistical analyses include non-parametric trend analyses, snowpack centroid analyses, and correlation analysis between datasets. Daily measurements of winter precipitation around the Tahoe basin from 1974-2012 and CPC/NCEP gridded daily precipitation analysis along the Sierra Crest for the period 1948-2012 are examined to diagnose the climatology of the vertical structure of water vapor flux above the Sierra Nevada during substantial wintertime precipitation events. NCEP/NCAR model reanalysis and soundings w Oakland were used to look at upper atmospheric conditions, including the presence of vapor transport by low- and mid-level jets on storm days as well as upstream static stability in relation to significant precipitation events.

## **Principal findings and significance**

- Total precipitation has remained constant at the study sites over the study period. The fraction of precipitation that fell as snow (as represented by snow water equivalent measurements) decreased over the study period. This could be significant if associated with a long term climate trend. Specifically:
  - total precipitation in the eastern Sierra Nevada has not changed since the 1960s;
  - the fraction of precipitation as snow has decreased since the 1960s; this fraction is dependent upon elevation; and
  - occurrence of early spring melt-out dates began in the 1990s.
- Using both Klieforth data and SNOTEL data we were able to diagnose the climatology of the vertical structure of water vapor flux above the Sierra Nevada during substantial wintertime precipitation events. Atmospheric River (AR) and nonAtmospheric River events (NAR) are analyzed to better understand the vertical structure of water vapor flux above the Sierra Nevada. The National Centers for Environmental Prediction-National Center for Atmospheric Research model reanalysis and soundings from Oakland

(KOAK) were used to look at upper atmospheric conditions, including the presence of vapor transport by low- and mid-level jets on storm days as well as upstream static stability in relation to significant precipitation events.

Key findings include:

- 1) AR produce a disproportionately large role in generating precipitation during the winter season in the Tahoe basin.
- 2) Strong mid-level vapor transport needs to occur in tandem with low-level transport in order to achieve the most extreme two-day precipitation in the Tahoe basin.
- 3) When low- to mid-level vapor transport is present on days with a defined AR, the magnification of two-day precipitation intensity decreases with distance from the Sierra Crest; on NAR days the relative increase in two-day precipitation intensity due to low- and mid-level vapor transport does not vary based on distance from the Sierra Crest.
- 4) AR and NAR moisture fluxes are significantly modified by upstream static stability.
- 5) Understanding the impacts of AR and their moisture flux structure from the lower through the middle troposphere are crucial components of the hydrometeorology in this highly volatile hydrological region.

## **Information Transfer Activities**

### **Conferences**

Backes, T. M.; Schumer, R. A.; Mejia, J. F.; Kaplan, M. L.; Redmond, K. T., (2013) Combined effect of mid-level jets and atmospheric rivers on winter precipitation in the eastern Sierra Nevada. American Geophysical Union Fall Meeting. San Francisco, CA.

### **Manuscripts**

Backes, T. M.; Kaplan, M. L.; Schumer, R. A.; Mejia, J. F. (in review). A Climatology of the Vertical Structure of Water Vapor Transport to the Sierra Nevada in Atmospheric River and nonRiver Wintertime Precipitation Events. Submitted to the Journal of Hydrometeorology.

## **Student Support**

This grant funded the Master's research of Tracy Backes. Funding also supported Tracy's presentation of research results at the 2013 American Geophysical Union Fall Meeting.



## Quantifying the Impact of Hyporheic Exchange on In-Stream Water Quality in the Truckee River, NV

### Basic Information

<b>Title:</b>	Quantifying the Impact of Hyporheic Exchange on In-Stream Water Quality in the Truckee River, NV
<b>Project Number:</b>	2011NV181B
<b>Start Date:</b>	3/1/2011
<b>End Date:</b>	2/28/2014
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV02
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Hydrology, Models, Water Quality
<b>Descriptors:</b>	Truckee River, Water Quality
<b>Principal Investigators:</b>	Rina Schumer

### Publications

1. Johnson, Z.C., J.J. Warwick, R. Schumer (2014a) "Factors affecting hyporheic and surface transient storage in a western U.S. river," J. Hydrology 510, 325-339.
2. Johnson, Z.C., R. Schumer, J.J. Warwick, Relative influence of hyporheic and surface transient storage on total N uptake kinetics. AGU Fall Meeting 2013, San Francisco, CA. Poster, B11C-0389.
3. Johnson, Z.C., J.J. Warwick, R. Schumer, Physical and biological N retention in two transient storage zones of the Truckee River, NV. UCOWR/NIWR Conference 2013, Lake Tahoe, CA. Poster.

**NIWR Project 2011NV181B**  
**Quantifying the Impact of Hyporheic Exchange on In-stream Water Quality in the Truckee River, NV**

**Problem and Research Objectives**

Hyporheic exchange, the mixing of surface water (SW) and groundwater (GW) beneath and adjacent to streams, can have a significant effect on water quality and aquatic habitat. In this zone, stream water residence times are increased which has a large effect on the fate and transport of solutes. Perhaps the most important function for the Truckee River is the removal of nitrogen through denitrification from the system as periphyton growth in the Truckee River is primarily nitrogen limited (Green, 2002). If hyporheic exchange is increased through current restoration efforts, total periphyton biomass should decrease and the minimum nighttime DO concentrations in the river should increase. Understanding the fluctuations of DO in this system are particularly important for the threatened and endangered habitat of the Lahontan cutthroat trout (threatened species) and cui-ui (endangered species) that historically made spawning runs from Pyramid Lake to the Truckee River.

Although the physics of hyporheic exchange are well understood, characterization of exchange over long reaches is difficult. For this reason, most hyporheic exchange studies have focused on relatively short reaches ranging from 300 m to 3.5 km. The proposed reach length on the Truckee River is approximately 56.5 km, stretching between Derby and Marble Bluff Dams. Apart from the challenges posed by the relatively large reach length, few studies have specifically focused on hyporheic exchange in the Truckee River even along short stretches (Knust and Warwick, 2009). We proposed to add hyporheic exchange to an existing model which was previously modified for the Truckee River.

Restoration efforts along the Truckee River plan to return the river to more natural conditions including the addition of stream meanders and pool-riffle sequences. Despite the fact that these projects are known to increase hyporheic exchange, the magnitude of influence towards in-stream water quality does not appear to have been addressed in previous studies. We will use knowledge gained about the hyporheic processes in the Truckee River and the factors controlling them to quantify the relative impact of these restoration efforts on the in-stream water quality.

**Methods**

We conducted dye, chloride and nitrogen tracer experiments in the Lower Truckee River to estimate the stream storage coefficient ( $\alpha$ ), the storage zone cross-sectional area ( $A_s$ ), dispersion ( $D$ ), the first-order decay coefficient for the stream ( $\lambda$ ), reaction characteristics, and travel times between measurement points. Data were analyzed and interpreted using versions of the OTIS solute transport code WASP water quality models modified specifically for this project. The models were used to characterize conservative and reactive transport in the Truckee, determine the relative influence of different transient storage zones on transport, and also to explore a variety of restoration scenarios on river nutrient uptake.

**Principal findings and significance**

- Hyporheic storage accounts for a significant fraction of solute residence time in small streams, which has been shown to have a large effect on the transport of solutes. It is not clear whether this characteristic is preserved in larger streams and rivers, as increased discharge and decreased slope may reduce overall exchange between the channel and

subsurface, and the size of surface storage zones may increase. Conservative tracer tests conducted in the Truckee River, a stream with mean annual discharge  $> 0.5 \text{ m}^3 \text{ s}^{-1}$ , were simulated with both one (1-SZ) and two-storage zone (2-SZ) transport models to quantify the relative role of surface transient storage (STS) and hyporheic transient storage (HTS) on the physical transport of solutes in a large stream. Tracer injections were conducted at two different discharge levels in two reaches with distinct geomorphic characteristics. STS was the dominant storage mechanism for all reaches and discharge levels and surface storage accounted for a larger fraction of median transport time ( $F_{MED}^{200}$ ) than hyporheic storage in all but one case. Increased discharge significantly reduced the influence of the HTS (primarily) and STS zones on median transport time at the study site. Comparisons with studies of discharge and geomorphic effects on TS characteristics in other streams indicated differing physical controls on STS and HTS zones. Therefore, measurements such as slope, sinuosity, width, depth, and gross gains and losses of discharge need to be considered along with discharge. This work adds to the growing sentiment that up-scaling and prediction of stream storage characteristics based on discharge and channel properties is far from straightforward. Since biogeochemical processing occurs differently in the HTS and STS, two-zone storage models provide necessary representations of transport in river systems for studies focused on aspects of water quality. Extra parameters are required for model optimization but simple cross-section surveys (area and velocity) provide enough information to ensure enhanced parameter reliability.

- The main channel (MC), surface transient storage (STS), and hyporheic (HTS) transient storage zones provide unique habitats in streams. Most nutrient spiraling studies employ models that aggregate the influence of the various transient storage zones on uptake and retention. This may explain contradictory results on drivers of nutrient cycling in streams. Here, a two-storage zone transport model with Michaelis-Menten uptake kinetics and a dynamic nutrient spiraling method (TASCC) are used to quantify the relative role of the three stream compartments on the physical and biological transport of solutes. The method is applied to co-injected conservative and reactive tracer tests in a stream with mean annual discharge  $> 0.5 \text{ m}^3 \text{ s}^{-1}$ . The relative influence of the three stream compartments on in-stream uptake of  $\text{NO}_3\text{-N}$  varied between reaches; each stream compartment dominated overall nitrate uptake in at least one sub-reach. HTS zones generally had greater influence on nitrate concentrations than STS zones because of longer residence times and faster uptake rates. However, a combination of geomorphology, MC-transient storage connectivity, residence time, compartment size, and uptake rate controls overall nutrient uptake capacity of a stream. Model simulations in which individual transient storage zones are removed indicate decreases in uptake and uptake efficiency in the MC and to a lesser degree in the second transient storage zone. The vast majority of this reduction in uptake was due to loss of biological uptake in either the STS or HTS zones, although HTS physical retention alone also had a significant effect on nitrate uptake.
- Wastewater treatment plants are common point sources of nutrients to streams. Excess loading of nutrients, particularly nitrogen (N), can result in significant water quality degradation. Where stream loading cannot be increased by effluent trading with other

point or nonpoint sources, stream restoration may be an alternative means for point sources to increase loading while maintaining or improving stream health by increasing in-stream N removal via denitrification. However, the primary drivers of nitrogen removal are currently not well understood and thus optimizing restoration efforts is difficult. A two-storage zone transport model with Michaelis-Menten uptake kinetics was applied to a river system based on the Truckee River of Nevada to simulate N removal for multiple restoration scenarios and different types of nitrogen loading. Rates of N removal were found to be most sensitive to the size of the hyporheic zone ( $A_{HTS}$ ) and maximum areal uptake rate in the hyporheic zone ( $U_{max,HTS}$ ), followed by the half-saturation concentration for denitrification ( $K_m$ ). A visual tool that incorporates the ranges of these three parameters indicates the potential effectiveness of restoration activities for increasing N removal. Combining restoration targets provided more N removal than the sum of N removal from the individual targets. The proximity of the restoration to the source did not significantly affect N removal in this study. The relative fractions of the three nitrogen species (dissolved organic-N, ammonium-N, and nitrate-N) was found to significantly affect a stream's potential to remove N. Together, these results can be used to help guide stream restoration activities to increase a stream's N removal capacity.

## **Information Transfer Activities**

### **Publications**

- Johnson, Z.C., J.J. Warwick, R. Schumer (2014c) "A numerical investigation of the primary drivers of in-stream N removal: Use of stream restoration for nutrient trading," *in preparation*.
- Johnson, Z.C., J.J. Warwick, R. Schumer (2014a) "Factors affecting hyporheic and surface transient storage in a western U.S. river," *J. Hydrology* **510**, 325-339.

### **Presentations**

- Johnson, Z.C., R. Schumer, J.J. Warwick, Relative influence of hyporheic and surface transient storage on total N uptake kinetics. AGU Fall Meeting 2013, San Francisco, CA. *Poster*, B11C-0389.
- Johnson, Z.C., J.J. Warwick, R. Schumer, Physical and biological N retention in two transient storage zones of the Truckee River, NV. UCOWR/NIWR Conference 2013, Lake Tahoe, CA. *Poster*.

### **Student Support**

This grant is funding the PhD research of Zachary Johnson. His dissertation defense is scheduled for June 17. This year he attended and presented material at the UCOWR/NIWR Conference and AGU Fall Meeting, published the first chapter of his dissertation (*Journal of Hydrology*), submitted the second chapter (*Limnology & Oceanography*), and is close to submitting his third chapter.

# Optimization of ozone-biological activated carbon treatment for potable reuse applications

## Basic Information

<b>Title:</b>	Optimization of ozone-biological activated carbon treatment for potable reuse applications
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<b>Start Date:</b>	3/1/2013
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<b>Principal Investigators:</b>	Daniel Gerrity

## Publication

1. Selvy, A., D. Gerrity. 2014. Optimization of Ozone-Biological Activated Carbon Treatment for Potable Reuse Applications. Nevada Water Resources Association 2014 Annual Conference, Las Vegas, NV, Jan. 2014.

**Project 2013NV194B**  
**Optimization of Ozone-biological Activated Carbon Treatment for Potable Reuse Applications**

## **1.0 Problem and Research Objectives**

In the face of climate change, pollution, and population growth, water scarcity has become a global threat. Many populations have witnessed their drinking water sources dwindle to an unsustainable level. These severe conditions have sparked interest in potable reuse as an increasingly viable alternative to typical ‘pristine’ drinking water sources. Although potable reuse has been practiced for decades, the public has become more supportive of the concept over the past few years based on the historical success of several benchmark facilities in the United States and abroad. Many municipalities are considering implementing their own projects, but there is considerable debate as to the level of treatment needed to ensure protection of public health.

Among existing potable reuse guidelines and regulations, the California Department of Public Health (CDPH) provides the most stringent requirements for water quality. Currently, the best way to meet these standards is through the use of full advanced treatment (FAT), which consists of reverse osmosis (RO) and an advanced oxidation process (AOP). Although extremely effective, RO is energy intensive and produces a concentrated brine solution that is both difficult to dispose of and an ecological concern in coastal regions. Alternative treatment trains composed of ozone and biological activated carbon (BAC) have been employed in several locations throughout the world, but these systems have not yet been optimized and are unable to compete with RO-based treatment trains on the basis of total organic carbon (TOC) removal and reductions in total dissolved solids (TDS). While RO-based treatment trains have been known to remove TOC to the  $\mu\text{g/L}$  level, ozone-BAC trains have yet to achieve this threshold. One example is the Fred Hervey Water Reclamation Plant in El Paso, TX, which produced an average effluent TOC concentration of 3.2 mg/L in 2011.

With the exception of TOC and TDS, which are generally more relevant to aesthetics rather than public health, ozone-BAC is capable of producing a water quality similar to that of RO-based treatment trains on the basis of pathogen reduction, trace organic contaminant mitigation, and a variety of other parameters. There are also significant energy and cost savings for the ozone-BAC alternative so there is an incentive to optimize such treatment trains to achieve greater TOC removal. This process requires up to 70% less capital costs and 80% less operation and maintenance (O&M) costs than FAT.

The purpose of this study is to optimize the ozone-BAC process for TOC removal with respect to ozone dose and empty-bed contact time (EBCT). The experiments are being performed in a one-liter per minute pilot-scale reactor at a local water reclamation facility. Over the next phase of the project, the effluent TOC concentration from parallel BAC columns will be compared against a 0.5 mg/L TOC benchmark value. CDPH established this benchmark as a conservative indicator for the removal of other regulated and unregulated chemical contaminants that may be found in wastewater. The simultaneous removal of trace organic contaminants will also be assessed.

Achieving these goals will provide water reuse agencies with a more cost-effective and sustainable alternative to FAT.

## **2.0 Methodology**

### **2.1 Pilot-Scale Reactor**

#### **2.1.1 Construction and Operation**

A 1 liter-per-minute (LPM) pilot-scale reactor was constructed at the City of Henderson's Southwest Reclamation Facility (SWRF). It consists of 12 ozone contactors and 5 BAC columns, which are used to treat full-scale membrane bioreactor (MBR) effluent. The flow rate through the system is measured with an in-line flow meter. The addition of spiking stocks (e.g., microbial surrogates and target compounds) or conservative tracers (e.g., sodium chloride) is achieved through a sample injection port followed by a static mixer. The water then travels to a Venturi injector where ambient air, concentrated oxygen, or ozone is introduced.

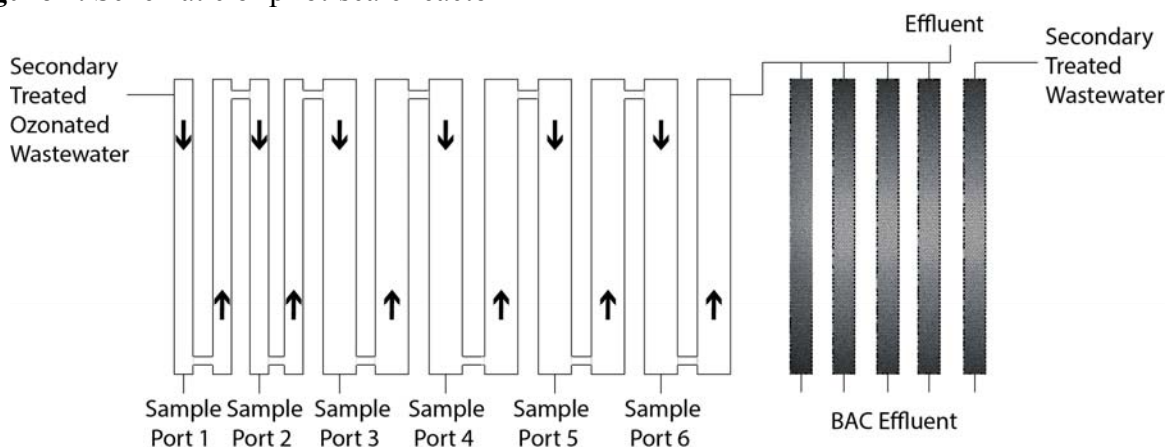
Concentrated oxygen is achieved with a portable system equipped with molecular sieves (AirSep, Denver, CO). The oxygen is generated at a flow rate of 2 LPM and a pressure of 20 psig. After passing through an air filter to remove particulates, the oxygen travels to a Nano dielectric ozone generator (Absolute Ozone, Edmonton, AB, Canada). The output from the ozone generator travels either through a bypass line to a catalytic destruct unit or to the Venturi where the ozone is injected into the process flow. The bypass line is controlled by a standard gas flow meter, and the feed gas line is monitored by a digital mass flow controller, which allows for precise control of ozone dosing. In addition to check valves, the feed gas line is equipped with a water trap that prevents water from entering the feed gas tubing and backing up into the generator. The ozonated water travels to the 12 ozone contactors connected in series; samples can be collected from sample ports located at the bottom of the contactors. Ozone off-gas is collected in Teflon tubing at the top of each contactor and is sent to a catalytic destruct unit. The ozone off gas line is also protected by a water trap that prevents water from reaching the catalytic destruct unit. The ozone concentration in the feed gas and off gas is determined by an ozone analyzer from IN USA (Norwood, MA). The difference in ozone concentration between the feed gas and off gas is coupled with the reading from the mass flow controller to determine the transferred ozone dose. A sample conditioner (IN USA) equipped with a vacuum pump is also installed upstream of the ozone analyzer to remove any moisture from the feed gas and off gas and to control the flow to the analyzer.

The effluent from the final ozone contactor flows into four parallel BAC columns that will ultimately be operated at different empty bed contact times (EBCTs). The pilot will soon be equipped with a fifth parallel column filled with a proprietary biocatalyst from LentiKat's Biotechnologies (Czech Republic). The biocatalyst is manufactured as a porous bead containing enzymes and microorganisms. The biocatalyst has historically been used in suspended growth (i.e., activated sludge) systems so this will be the first evaluation of the biocatalyst in a packed-bed configuration. A separate control BAC column receives pilot influent (i.e., MBR filtrate) and allows for the evaluation of effluent organic matter (EfOM) removal with and without the

synergistic effects of ozonation. An experimental BAC column, the biocatalyst column, and the control BAC column will all be operated at the same EBCT to allow for direct comparisons of treatment efficacy. The BAC columns contain exhausted Filtrasorb 300 (F300; Calgon Carbon, Pittsburgh, PA), which was provided by the Upper Occoquan Service Authority (Fairfax County, VA). Sample ports are located at the bottom of each column, and the flow rates are controlled by independent needle valves. Activated carbon samples can also be collected periodically from dedicated sample ports to evaluate the development of the microbial community. The microbial community in the BAC columns will be discussed in Section 2.1.2.

Figure 1 illustrates the layout of the pilot-scale reactor, and corresponding photos of the ozone contactors and BAC columns are provided in Figures 2A and 2B, respectively.

**Figure 1.** Schematic of pilot-scale reactor



**Figure 2.** Photos of the (A) ozone contactors and (B) BAC columns

A.



B.





### 2.1.2 Operational Issues

During the startup phase, the project team encountered several issues that required operational modifications and hindered the development of the microbial community in the BAC columns. These are summarized below:

1. The pressure buildup in the off gas tubing creates an air pocket at the top of ozone contactor 11, which causes the water level to drop and reduces overall contact time. This does not have a significant impact on operation, but it requires an adjustment to the hydraulic residence time in the reactor. The problem can be mitigated by manual valve adjustments and continuous operation of the sample conditioner and associated vacuum pump. This creates suction in the off gas tubing and reduces the pressure buildup in ozone contactor 11.
2. Periodic backwashing of the BAC columns is required to reduce headloss in the system. During backwashing, the carbon tends to stick together and rise as a single plug, which reduces the efficacy of the backwash cycle. Gentle tapping with a rubber mallet was implemented during backwashing to facilitate dispersion of the carbon. Air scour would be implemented in large-scale ozone-BAC applications to achieve the same result.
3. The BAC columns are equipped with mesh screens at the top and bottom to prevent loss of BAC through the effluent line during normal operation and through the influent line during backwashing. Microbial growth and accumulation of biopolymers was observed on the mesh screens, which reduced flow through the columns. More frequent backwashing and cleaning of the mesh screens was implemented to mitigate this problem.
4. Several issues beyond the control of the project team also resulted in project delays. The initial contractual phase between UNLV and the City of Henderson resulted in a slight delay of reactor construction. In addition, the full-scale ultraviolet (UV) disinfection reactors at the City of Henderson facility required maintenance to repair broken bulbs, which resulted in the shutdown of feed water to the pilot-scale ozone-BAC reactor. Because a continuous supply of water and EfOM is required for the development of the microbial communities in the BAC columns, this resulted in project delays. The feed line to the pilot-scale reactor has since been moved to allow for a continuous supply.
5. Practical limitations also hindered the development of the microbial communities. These issues were identified after observing the lack of TOC removal through the BAC columns after several weeks of operation. During startup of typical biological filtration systems, TOC removal increases gradually until a certain threshold is achieved—typically 20-40% TOC removal after 2-3 months. However, the TOC in the BAC influent versus effluent remained essentially unchanged, thereby indicating a lack of bacteria or overly recalcitrant EfOM. Membrane bioreactors offer a highly effective biological treatment process for EfOM, nutrient, and pathogen removal. Therefore, they offer an effective and robust treatment barrier for potable reuse applications, but they hinder the startup of biological filtration systems for two reasons:
  - a. The membrane component of the MBR eliminates nearly all bacteria from the filtrate so an external source of bacteria was required for the BAC columns. Secondary effluent from a different wastewater treatment plant

was pumped through the columns for seven days to facilitate colonization of the carbon.

- b. Initially, the goal was to develop the microbial community without the use of ozone. This would allow the project team to identify a TOC removal baseline from which the synergistic impacts of ozone could be quantified. However, the MBF filtrate proved to be overly recalcitrant, and the bacteria were not being provided with a suitable carbon source. Potential solutions included seeding the reactors with an alternative carbon source, such as acetate or methanol, or implementing ozonation to transform the recalcitrant EfOM into a more bioavailable supply. Continuous ozonation was identified as the preferred alternative.

After encountering and addressing these various issues, the pilot-scale system is now operating as expected, and the project team is observing reductions in TOC through the BAC columns. Preliminary results are presented in Section 3. Once the reductions in TOC reach their asymptotic value, which indicates that the microbial community has stabilized, the experimental EBCTs will be implemented, and the effects of different operational conditions will be systematically evaluated.

## **2.2 Methodology for the Evaluation of Reactor Hydraulics**

Step input tracer studies can be performed to characterize the hydraulics of a system. In these studies, a conservative chemical (i.e., one that will not react or be biodegraded), such as a salt, is added continuously at a sufficiently high concentration to allow it to be distinguished from the background concentration of the process water. The feed is then stopped after a certain amount of time. In the pilot-scale reactor, a tracer can be added at the injection port located at the upstream end of the system. The concentration of the tracer or another indicator parameter, such as UV absorbance for organic chemicals or electrical conductivity for salts, is then measured at specific points within the reactor and at a sufficient frequency to capture the initial appearance, sustained concentration, and disappearance of the tracer. After analyzing the data, the hydraulic retention time (HRT) of the system can be determined and compared against the theoretical HRT. The comparison of the experimental versus the theoretical HRT indicates whether there is excessive short-circuiting or lags within the reactor, which can adversely impact treatment efficacy.

For this study, sodium chloride (NaCl) was used as the tracer, and the concentration of the tracer was based on electrical conductivity. The target concentration of the tracer was twice the background conductivity of the process water. The tracer was added at 0.8 L/min using a peristaltic pump for a period of time equal to four times the theoretical HRT. Samples were collected and measured for conductivity at intervals dictated by the step input duration. The process was repeated for each ozone contactor sample port and for the overall system.

### 2.3 Methodology for Ozone Demand Decay Testing

An ozone demand decay study was performed on the source water using the indigo trisulfonate colorimetric method for dissolved ozone. Potassium indigo trisulfonate is dark blue in color but will quickly decolorize in the presence of ozone as the chemical is oxidized. A spectrophotometer is used to determine the absorbance of the indigo trisulfonate solution at 600 nm, which is directly related to the strength of the blue color. The extent of decolorization, or bleaching, during ozonation is directly correlated with the dissolved ozone concentration. Using this method, the dissolved ozone concentration can be determined at various points within the reactor or in a batch configuration to evaluate the interaction of ozone, EfOM, and target contaminants. For example, the transferred ozone dose (as determined by the feed gas flow rate and the reading from the ozone analyzer) can be compared to the dissolved ozone concentration at the end of the first contactor to determine the ozone demand of the water. The dissolved ozone concentration at the remaining sample ports can be used to characterize the decay of ozone over time, which is matrix specific. This demand decay process can be used to calculate the total ozone 'Ct', or ozone exposure, which is a common metric used to estimate pathogen inactivation.

For this study, a preliminary ozone demand decay test was performed in a batch configuration:

1. Five gallons of source water were collected and ozonated at the following ozone to TOC ( $O_3/TOC$ ) ratios: 0.25, 0.5, 1.0, and 1.5.
2. 10 mL of potassium indigo trisulfonate test solution were added to several 100 mL volumetric flasks that had been previously weighed.
3. The ozonated source water was added to a single flask at specified time steps (every 30 seconds for the first 2 minutes, every minute for the next 8 minutes, and then every 2 minutes thereafter). A sufficient sample volume was added to each flask to invoke a noticeable color change due to the combined effects of oxidation and/or dilution.
4. The flasks, which now contained indigo trisulfonate plus sample, were weighed to determine the mass of sample added, which was later converted to volume.
5. The absorbance of each sample was then measured with a spectrophotometer.
6. The absorbance of each sample was then converted to a dissolved ozone concentration using the following equation:

$$O_3(\text{mg/L}) = \frac{V_{\text{blank+indigo}} \times \text{Absorbance}_{\text{blank}} - V_{\text{sample+indigo}} \times \text{Absorbance}_{\text{sample}}}{f \times V_{\text{sample}} \times b} \quad (\text{Eq. 1})$$

where  $f$  represents the proportionality constant (0.42) and  $b$  is the cell path length (1 cm).

### 2.4 Methodology for EfOM Characterization with UV Absorbance and Fluorescence

When light of a certain wavelength is passed through a sample, some of the molecules in the sample absorb the light. When photons are absorbed, the absorbing molecule enters an excited state, meaning that the outer electrons transition to a higher energy level. Only a fraction of the incident photons are absorbed by molecules in the solution, and the remaining fraction passes through the solution. Using a spectrophotometer, the intensity of the transmitted radiation ( $I$ ) is compared with that of the incident radiation ( $I_0$ ), which yields the absorbance or transmittance of

the sample (Horiba Scientific, 2012). Wavelength-specific absorbance—typically at 254 nm—is often used as an indicator of water quality. Evaluating absorbance across the UV spectrum also provides a means of characterizing the EfOM in a sample.

Fluorescence can also be used to assess water quality and characterize EfOM. When the excited electrons eventually relax to their ground state, they release energy in the form of light (i.e., fluorescence). The intensity of the emitted light, which is characterized by a longer wavelength (i.e., less energy) than the incident light, is measured by a spectrofluorometer. These excitation-emission couples can be evaluated across a broad spectrum to generate an excitation emission matrix (EEM), or fluorescence ‘fingerprint’, for a water sample.

For this study, UV absorbance (or transmittance) and fluorescence were determined with a Horiba Aqualog spectrofluorometer (Edison, NJ). Samples were collected from each of the BAC columns, the pilot influent, and the pilot effluent. The samples were brought to room temperature and filtered using a 0.7- $\mu\text{m}$  GF/F Whatman syringe filter (GE Healthcare Life Sciences, Piscataway, NJ). Data were processed using Matlab (MathWorks, Natick, MA) to generate contour plots and identify critical fluorescence peaks and regional intensities.

## **2.5 Methodology for EfOM Quantification based on Total Organic Carbon**

A Shimadzu TOC V-csn (Kyoto, Japan) is being used for TOC analysis. This instrument measures total organic carbon using the non-purgeable organic carbon (NPOC) method. Acid is added to the sample to decrease the pH and convert inorganic carbon (i.e., carbonate species) to  $\text{CO}_2$ , and then the sample is purged with hydrocarbon-free compressed air to eliminate the  $\text{CO}_2$ . The sample is then sent to a combustion chamber where the remaining organic carbon is converted to  $\text{CO}_2$ . At this point, the  $\text{CO}_2$  is sent to a non-dispersive infrared detector and analyzed, and the signals are correlated to TOC concentration.

For this study, all glassware was cleaned according to the guidelines provided in Standard Method 5310B. The samples were collected in amber vials and kept cool prior to analysis. After the samples were acidified using 3N HCl to reduce the pH to less than 2, the samples were loaded in the autosampler and analyzed.

## **2.6 Methodology for the Evaluation of Biological Activity based on ATP**

Adenosine triphosphate (ATP) is a compound used by living organisms to store and transfer energy. When ATP reacts with the Luciferase enzyme, light is produced. This light can be measured with a luminometer to determine the concentration of ATP in the sample. The concentration of ATP can be used as an indicator of the presence of bacteria or the degree of biological activity in a system.

A deposit and surface analysis ATP test kit (Hach, Loveland, CO) was used to quantify the biological activity of the biofilm on the BAC. This method measures both the intracellular ATP found inside living bacteria as well as ATP dispersed in the sample from decayed biomass. The process used for the analysis is described below:

1. On February 24, 2014, media samples were extracted from the dedicated sample ports on the BAC columns using sterile instruments. Control BAC that had been stored in the refrigerator upon receipt from the Upper Occoquan Service Authority was also collected to compare with the BAC from the pilot-scale reactor.
2. 1 g of dry media was added to individual test tubes.
3. 5 mL of UltraLyse 7 was added to the tubes, and the tubes were capped. The tubes were inverted several times for mixing and allowed to sit for 5 minutes to ensure that the ATP was extracted from the lysed bacteria.
4. 1 mL of the resulting liquid (no solids) was transferred to another tube containing 9 mL of UltraLute (for dilution).
5. 100  $\mu$ L of the new solution were transferred to another tube containing 100  $\mu$ L of Luminase.
6. The final sample tube was placed in a PhotonMaster luminometer for analysis within 30 seconds.

The results of this preliminary testing are described in Section 3. The ATP assay will be repeated throughout the remainder of the project to assess changes in ATP over time. These results will ultimately be correlated with the degree of TOC removal through the BAC columns.

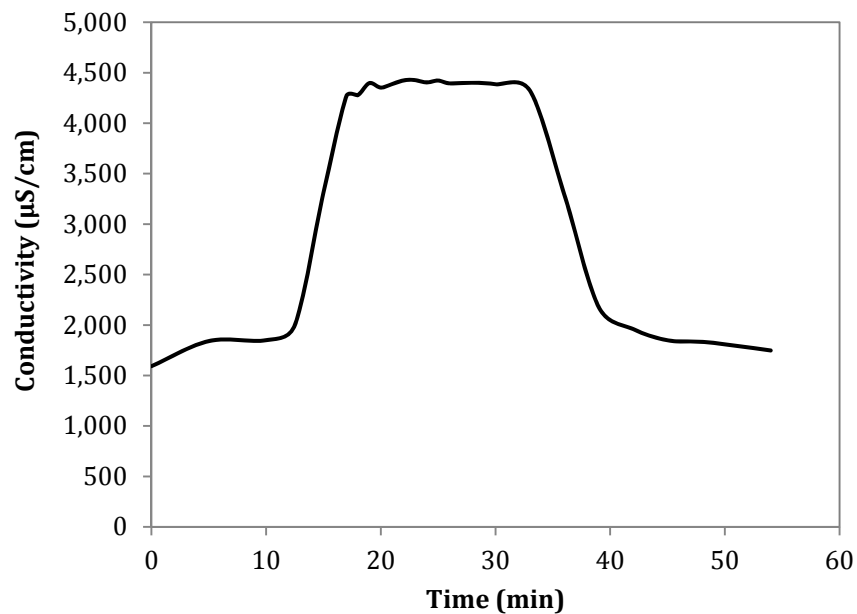
### **3.0 Principal Findings and Significance**

#### **3.1 System Hydraulics**

The overall system tracer curve can be seen in Figure 3. This shape reveals that the system performs similar to an ideal reactor. Theoretically, the slope of the curve as the tracer reaches the sample port should approach infinity, and the slope of the curve as the tracer leaves the sample port should approach negative infinity. The actual HRT can also be determined based on the time required for the tracer to initially arrive at the sample port or the time for the tracer to return to the background concentration after the feed is shut off. A comparison of the actual HRTs ( $t$ ) and the theoretical HRTs ( $\tau$ ) are provided in Table 1. Except for the first sample port (possibly due to error in measuring reactor volume through the influent tubing and Venturi injector), the values are very similar, thereby indicating a valid reactor design with minimal short-circuiting.

As mentioned earlier, these values will assist in determining the ozone exposure, or  $Ct$ , values for each ozone contactor. Given that a peristaltic pump was used for the tracer study, a higher flow rate was necessary to provide a relatively steady flow rate. For this reason, 0.8 LPM was used. However, typically the tracer flow rate should be significantly lower than the flow rate of the system so as to have little impact on the operation of the reactor. The system has a flow rate of 1 LPM meaning that with the addition of the tracer, the flow rate was nearly doubled. Since this scenario does not accurately reflect standard operational conditions that will be experienced, there may be some deviation from the true hydraulic retention times of the system. In some studies, lower hydraulic efficiencies have been witnessed at lower system flow rates and are thought to be due to an increase in dead space. This will be considered when determining  $Ct$  values.

**Figure 3.** Overall System Tracer Curve



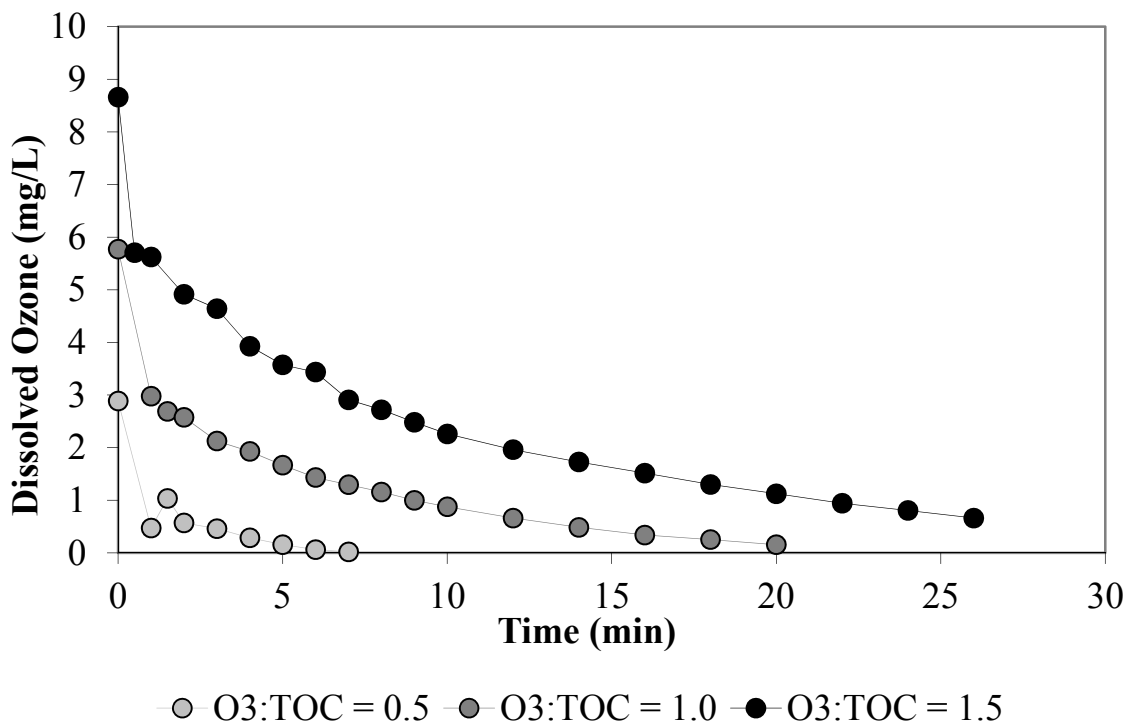
**Table 1.** Actual ( $t$ ) and theoretical ( $\tau$ ) HRTs at various locations in the system ( $Q = 1.8$  LPM)

Location	$t$ (min)	$\tau$ (min)	$t/\tau$
Sample Port 1	0.48	0.30	1.60
Sample Port 2	1.19	0.90	1.32
Sample Port 3	2.19	2.40	0.91
Sample Port 4	4.01	4.80	0.84
Sample Port 5	6.66	7.10	0.94
Sample Port 6	9.67	9.50	1.02
System	10.19	10.60	0.96

### 3.2 Ozone Demand Decay

Ozone demand decay curves were generated for  $O_3/TOC$  ratios of 0.5, 1.0, and 1.5 (Figure 4). It was not possible to generate a demand decay curve for the  $O_3/TOC$  ratio of 0.25 because the instantaneous ozone demand exceeded the transferred ozone dose.

**Figure 4.** Ozone Demand Decay Curves for the MBR Filtrate as a Function of  $O_3/TOC$  Ratio



The curves indicate the rate at which the ozone decays in this particular water source. This gives insight into the composition of the water (i.e., presence and complexity of organic matter). The extended period of time necessary for the complete decay of ozone in the target water matrix indicates that the 9.5 mg/L of TOC is likely recalcitrant.

Ozone constants for various trace organic contaminants can be found in the literature, or determined experimentally, and used in conjunction with  $Ct$  values to determine the amount of removal that is expected. This is also true for the log inactivation of microorganisms, which require certain ozone exposures for various levels of removal. Higher  $Ct$  values generally constitute improved water quality through the inactivation of microorganisms along with the oxidation of organic matter. Naturally, the higher the ozone dose, the more exposure received. However, the additional removal after a certain point becomes unsubstantial, which is where the need for optimization stems from. From Table 2, it can be seen that with a 0.25  $O_3/TOC$  ratio the entire applied ozone dose is consumed before exiting the system. Whereas, employing a 1.5  $O_3/TOC$  ratio provides extremely high exposures that are perhaps unnecessary.

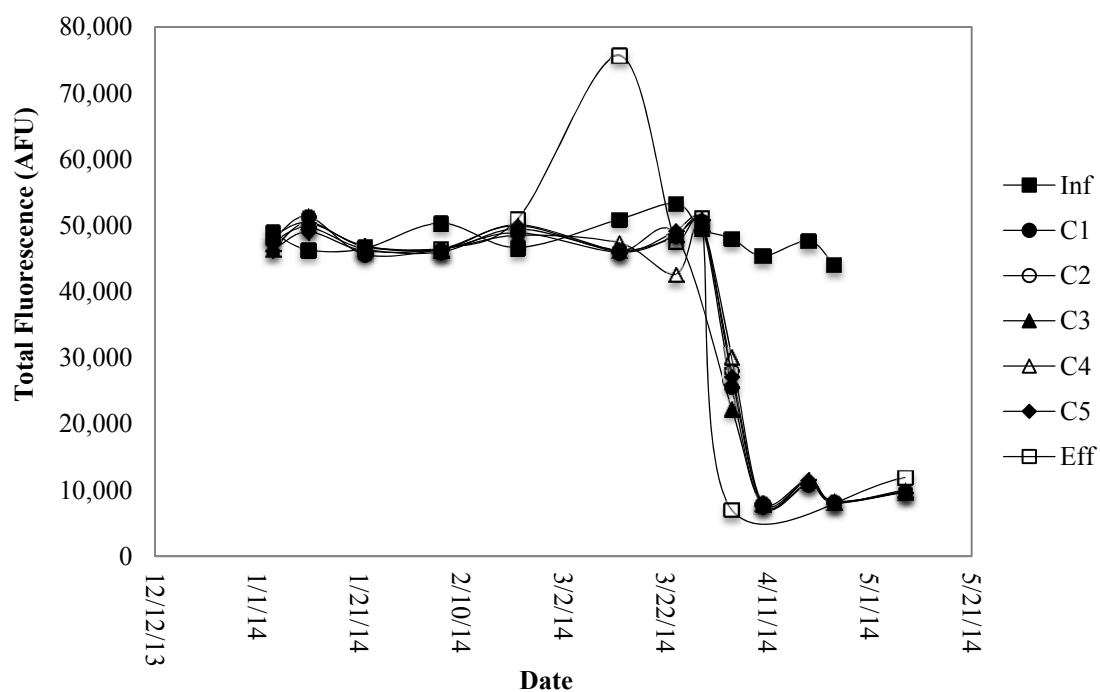
### 3.3 UV Absorbance and Fluorescence

The UV absorbance at 254 nm (i.e.,  $UV_{254}$ ) and total fluorescence (reported in arbitrary fluorescence units (AFU)) for the samples collected from 1/4/14 to 5/8/14 are illustrated graphically in Figures 5 and 6. Although the values fluctuate over time, there is a general trend that can be observed. All of the sample locations exhibited  $UV_{254}$  absorbances of approximately  $0.15 \text{ cm}^{-1}$  and total fluorescence values of approximately 49,000 AFU—consistent with the

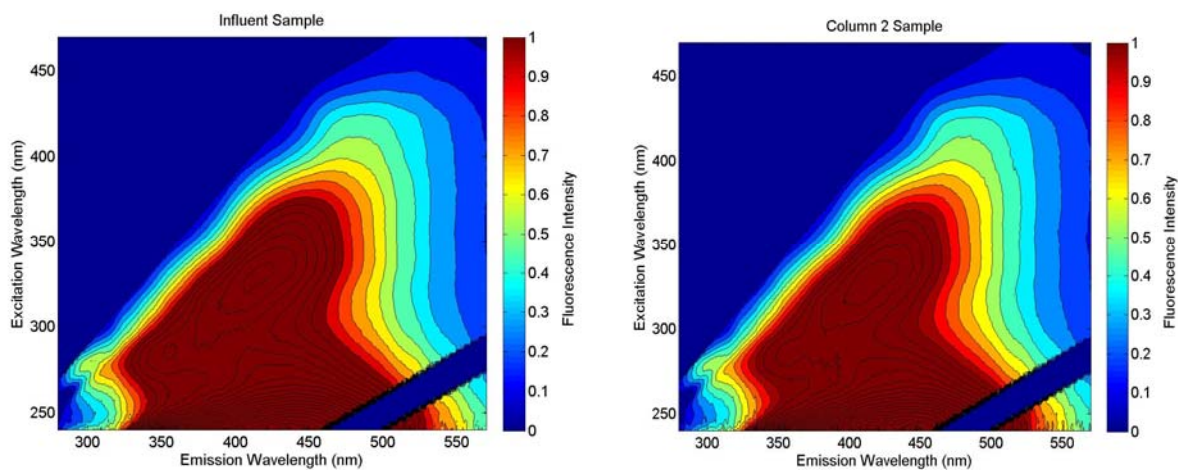




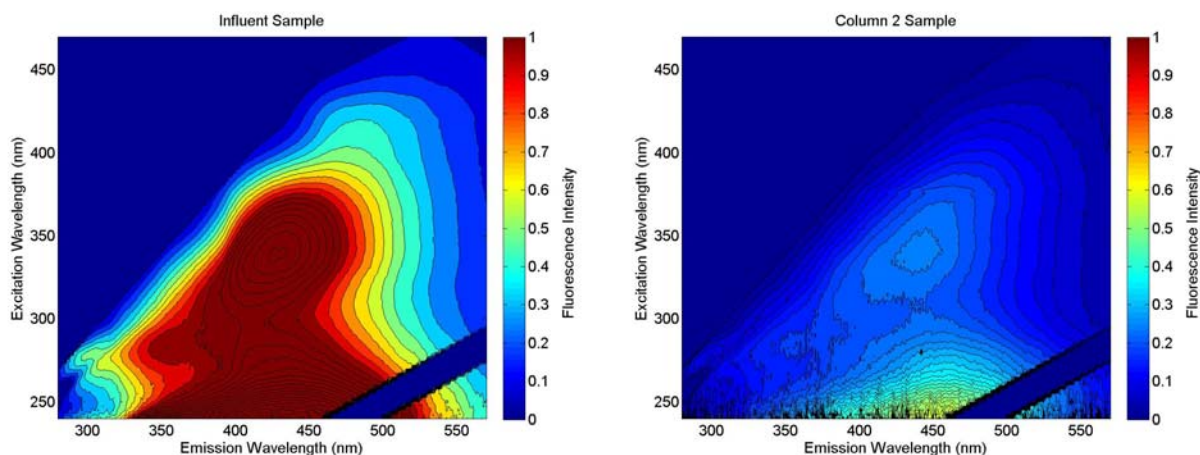
**Figure 6.** Historical Fluorescence Data for the Pilot-Scale Ozone-BAC System



**Figure 7.** Fluorescence EEMs for the Influent and Column 2 Samples Taken from the Pilot-Scale Ozone-BAC System on 3/24/14. No change was observed due to the lack of microbial activity in the BAC column.



**Figure 8.** Fluorescence EEMs for the Influent and Column 2 Samples Taken from the Pilot-Scale Ozone-BAC System on 05/08/14. A significant reduction in fluorescence was observed due to ozonation of the MBR filtrate (i.e., pilot influent).

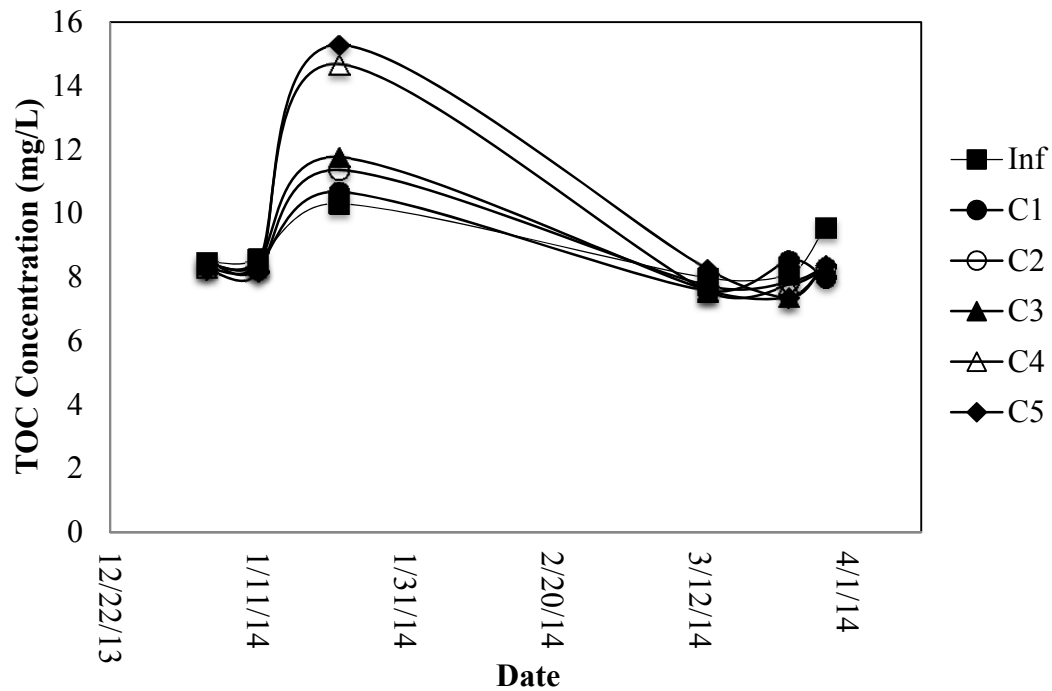


### 3.4 TOC

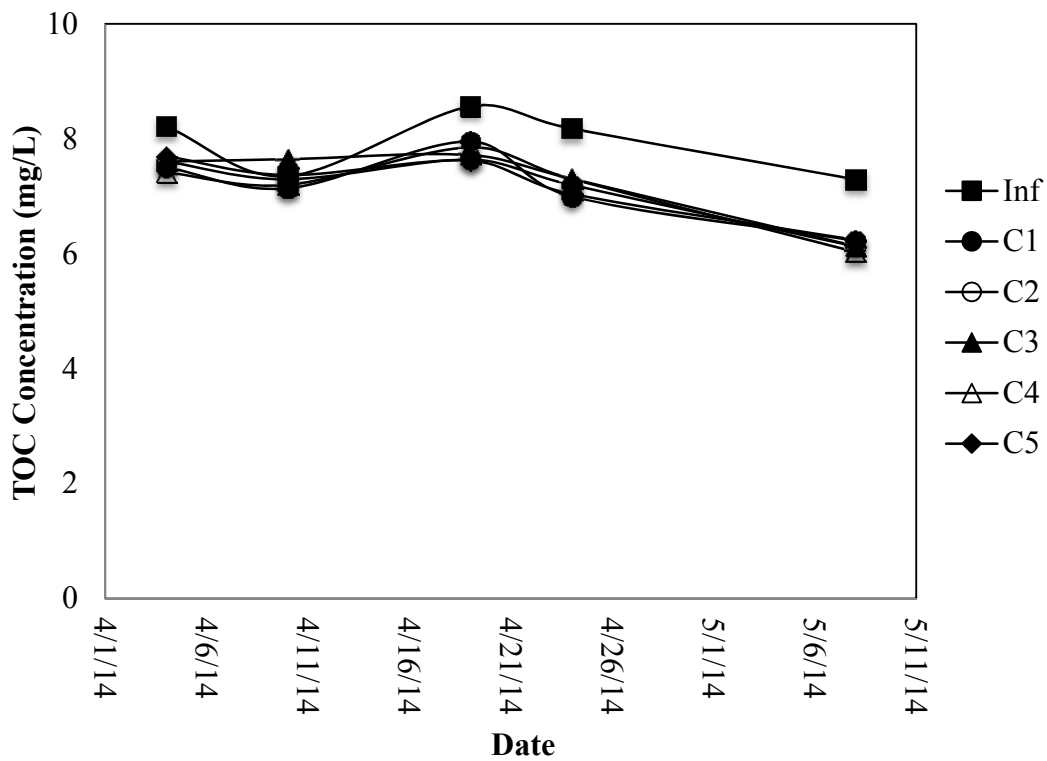
Figure 9 provides a graphical representation of the TOC concentration at various points in the system from 01/04/14 to 03/29/14. Excluding experimental variability, the TOC did not change in the influent versus the BAC effluent, which indicates a lack of microbial activity. Bacteria consume organic compounds as an energy source for cell synthesis. With a sufficient microbial community, the TOC concentrations in the BAC effluent would be lower than those of the influent water. Since there is typically 8 mg/L of TOC in the source water, this should provide sufficient substrate for biological growth. However, the lack of TOC removal implies that the EfOM in the MBR filtrate is recalcitrant and cannot be easily biodegraded by microorganisms. Due to this fact, the ozone generator was started on 4/4/14 and has been run continuously since that time.

Figure 10 provides a graphical representation of the TOC concentration at various points in the system from 04/04/14 to 05/08/14 (i.e., after the initiation of ozonation), and Table 2 summarizes the TOC removal during the same time period. Immediately after startup of the ozone generator, the TOC did not exhibit the same changes that were observed for  $UV_{254}$  absorbance and total fluorescence because ozonation is insufficient to induce significant mineralization (i.e., conversion of organic carbon to  $CO_2$ ). However, the new food source is aiding the development of the microbial community, which is indicated by the gradual increase in TOC removal through the BAC columns over time. This will also be verified with ATP analyses, which are described in the next section.

**Figure 9.** TOC Concentrations Prior to Startup of the Ozone Generator



**Figure 10.** TOC Concentration after Startup of the Ozone Generator



**Table 2.** Summary of TOC Removal through the BAC after Startup of the Ozone Generator

Location	Percent Removal				
	4/4/14	4/10/14	4/19/14	4/24/14	5/8/14
Column 1	9.5	3.0	7.7	17	17
Column 2	8.1	0.8	12	14	19
Column 3	8.0	-3.8	11	12	19
Column 4	11	2.1	9.1	12	21
Column 5	6.8	-0.2	12	16	17

### 3.5 ATP

The results from the preliminary ATP analysis on 2/24/14 (prior to startup of the ozone generator) are tabulated in Table 3. It is apparent that there is an increase in ATP compared to the control sample, but it is not possible to determine whether the ATP is from decayed microorganisms or live bacteria. Although there appears to be some bacterial growth occurring, typical values from the literature (Table 4) are much higher than those observed in the current study. Based on these values, it is apparent that the microbial community was grossly underdeveloped at the time the samples were collected. However, the values are expected to increase significantly when the ATP analysis is repeated considering that the ozone system is now operating, and biological activity in the BAC columns appears to be increasing.

**Table 3.** Summary of the ATP Analysis of the BAC

Sample	Filled Tube Weight (g)	Empty Tube Weight (g)	Media Weight (g)	ATP (pg ATP/g media)
Control BAC	13.0	11.8	1.19	62.7
Column 1	12.8	11.7	1.14	657
Column 3	12.7	11.7	0.926	228
Column 5	13.0	11.7	1.33	290

**Table 4.** Typical ATP Concentrations in Biological Filters

Sample Source	ATP (pg ATP/g media)	Reference
75 day old GAC from pilot study	1.8E+06	(Velten et al., 2007)
90 day old GAC filter from pilot study	0.8E+06 - 1.8E+06	(Velten et al., 2011)
30 GAC filters from 9 WWTPs	0.1E+05 - 2.5E+05	(Magic-Knezev & van der Kooij, 2004)

### **3.6 Future Work**

In the next phase of the project, the following tasks will be completed:

- Evaluation of biological activity in the BAC columns based on ATP, TOC, and EfOM characterization.
- Evaluation of O<sub>3</sub>/TOC ratios of 0, 0.25, 0.50, 1.00, and 1.50 for EfOM transformation, trace organic contaminant oxidation, and correlations between these parameters.
- Evaluation of EBCTs of 0, 5, 10, 15, and 30 minutes based on TOC and trace organic contaminant removal.
- Optimization of ozone-BAC with respect to O<sub>3</sub>/TOC ratio and EBCT.
- Evaluation of a proprietary biocatalyst.
- Quantification of total and fecal coliforms in the pilot influent and effluent.

### **5.0 Information Transfer Activities**

1. Selvy, A., D. Gerrity. 2014. Optimization of Ozone-Biological Activated Carbon Treatment for Potable Reuse Applications. Nevada Water Resources Association 2014 Annual Conference, Las Vegas, NV, Jan. 2014. (2<sup>nd</sup> Place in Student Poster Contest) (see Appendix)

### **6.0 Student Support**

This grant largely funded the research endeavors (time, instruments and travel) during completion of Ashley Selvy's M.S.E. degree. Ashley is expected to graduate in May 2015. Ashley presented a poster at the Nevada Water Resources Association 2014 Annual Conference and was awarded 2<sup>nd</sup> Place in the student poster competition. A team of senior design students was also advised by Dr. Gerrity in the spring 2013 semester in which they designed a potable reuse treatment facility based on advanced oxidation and biological activated carbon for Searchlight, Nevada. During the summer of 2014, an undergraduate student will assist Ashley Selvy in operation of the pilot-scale system at the City of Henderson Southwest Water Reclamation Facility.

### **7.0 References**

1. Gerrity, D., Gamage, S., Holady, J.C., Mawhinney, D.B., Quinones, O., Trenholm, R.A. and Snyder, S.A. (2011) Pilot-scale evaluation of ozone and biological activated carbon for trace organic contaminant mitigation and disinfection. *Water Research* 45, 2155-2165.
2. Gerrity, D., Owens-Bennett, E., Venezia, T., Stanford, B.D., Plumlee, M.H., Debroux, J., Trussell, R.S. (2014) Applicability of ozone and biological activated carbon for potable reuse. *Ozone Sci. Eng.* 36, 123-127.
3. Magic-Knezev, A., & van der Kooij, D. (2004). Optimisation and significance of ATP analysis for measuring active biomass in granular activated carbon filters used in water treatment. *Water Research* , 38, 3971-3979.
4. Reungoat, J., Escher, B.I., Macova, M., Argaud, F.X., Gernjak, J.K. and Keller, J. (2012) Ozonation and biological activated carbon filtration of wastewater treatment plant effluents. *Water Research* 46, 863-872.

5. Reungoat, J., Macova, M., Escher, B.I., Carswell, S., Mueller, J.F. and Keller, J. (2010) Removal of micropollutants and reduction of biological activity in a full scale reclamation plant using ozonation and activated carbon filtration. *Water Research* 44, 625-637.
6. Snyder, S.A., von Gunten, U., Amy, G. and Debroux, J. (2014) Use of ozone in water reclamation for contaminant oxidation. WRF-08-05. WaterReuse Research Foundation.
7. Velten, S. (2011). Development of biomass in a drinking water granular active carbon (GAC) filter. *Water Research* , 45, 6347-6354.
8. Velten, S. (2007). Rapid and direct estimation of active biomass on granular activated carbon through adenosine tri-phosphate (ATP) determination. *Water Research* , 41, 1973-1983.

# Optimization of Ozone-Biological Activated Carbon Treatment for Potable Reuse Applications

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## INTRODUCTION

In the face of climate change, pollution, and population growth, water scarcity has become a global threat. Many populations have witnessed their drinking water sources degrade to an untenable level. These populations are often in arid regions with limited access to increasingly valuable alternative to typical 'pristine' drinking water sources. Although potable reuse has been practiced for decades, the public has become more supportive of the concept over the past few years based on the historical success of several benchmark facilities in the United States and abroad.

There is considerable debate as to the level of treatment needed to ensure protection of public health with regards to potable reuse. Among existing potable reuse guidelines and regulations, the California Department of Public Health (CDPH) provides the most stringent requirements for water quality. Currently, the best way to meet these requirements is through a combination of treatment (PAT). Figure 1 provides an example of the typical PAT layout.



Figure 1: Typical PAT system schematic (e.g., Orange County Water District)

Issues concerning PAT systems:

- High capital and O&M costs
- Energy intensive
- Disposal of concentrated brine stream

Alternative treatment trains composed of ozone and biological activated carbon (BAC) have been employed in several locations throughout the world, but these systems have not yet been optimized and are unable to compete with RO-based treatment trains on the basis of pathogen reduction, trace organic contaminant (TOC) removal, and dissolved solids (TDS). The layout of ozone-BAC treatment is depicted in Figure 2.

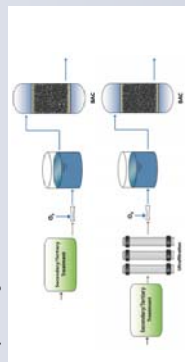


Figure 2: Ozone-BAC system schematics (e.g., El Paso and Gwinnett Counties)

With the exception of TOC and TDS, which are generally more relevant to aesthetics rather than public health, ozone-BAC is capable of removing pathogens, TOC, and PO<sub>x</sub>. Ozone-BAC is also capable of reducing the risk of pathogen reduction, trace organic contaminant (TOC) mitigation, and a variety of other parameters (Reungoat et al., 2010, 2012; Gerrity et al., 2011, 2014). There are also significant energy and cost savings for the ozone-BAC alternatives so there is an incentive to optimize such treatment trains to achieve greater TOC removal (Gerrity et al., 2014; Snyder et al., 2014).

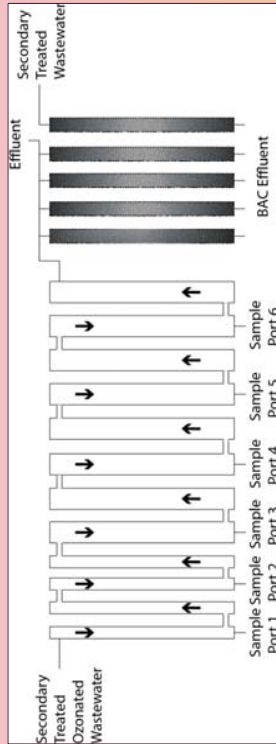


Figure 3: Pilot system schematic

## OBJECTIVES

This study aims to identify necessary pre-treatment, post-treatment, and operational conditions needed for ozone-BAC treatment trains to compete with PAT with regards to TOC reduction, pathogen inactivation and removal, and trace organic contaminant mitigation. According to the Groundwater Replenishment Reuse Regulations set by CDPH in 2013, potable reuse supplies should not contain more than 0.2 mg/L of wastewater-derived TOC. Optimization of the pilot system will be based on the detection of the best TOC detection time (EBCT) will be explored based on this 0.5 mg/L threshold.

## SYSTEM DESCRIPTION

- Membrane bioreactor filtrate feeds the 1 liter per minute pilot system
- A mass flow controller and venturi injector are used for ozone dosing.
- The pilot system consists of two 1.2-inch diameter and provide a total of approximately 17 minutes of contact time
- Exhausted Calgon carbon from the Upper Occoquan Service Authority is loaded into parallel 1-inch columns with a range of EBCTs
- The BAC has been seeded with secondary effluent from a local wastewater treatment facility, and the biofilm is developing
- A peristaltic pump is used for backwashing the BAC columns and for tracer and challenge studies

## OZONE DEMAND DECAY

An ozone demand decay study was performed on the MBR filtrate using the indigo tri sulfonate colorimetric method for dissolved ozone (Figure 4). The O<sub>3</sub> TOC of 0.25 was not graphed because the instantaneous ozone demand (IOD) exceeded the applied ozone dose (i.e., ozone CT ~ 0 mg-min/L).

## HYDRAULIC DETERMINATION

A sodium chloride step input tracer study was performed on the ozone contactors to characterize the hydraulics of the system. The tracer was quantified based on chloride conductivity. This will aid in the determination of ozone CT through each contactor.

Figure 5: Total system residence time distribution

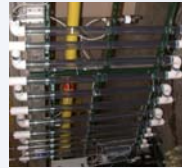
Location	t (min)		t (min)		t (min)	
	Q = 2 lpm	Q = 2 lpm	Q = 2 lpm	Q = 2 lpm	Q = 1 lpm	Q = 1 lpm
Port 1	0.48	0.30	0.30	0.50		
Port 2	1.19	0.90	0.90	1.40		
Port 3	2.19	2.40	2.40	3.80		
Port 4	4.01	4.80	4.80	7.70		
Port 5	6.66	7.10	7.10	11.5		
Port 6	9.67	9.50	9.50	15.3		
System	10.19	10.60	10.60	17.20		

## Economic Justification (10-MGD Comparison)

Capital (\$M)		Annual O&M (\$M)		Process		Capital (\$M)		Annual O&M (\$M)	
MF	\$11.4	\$1.5	MF	\$11.4	\$1.8				
HO	\$22.8	\$3.3	Ozone	\$5.4	\$0.1				
UV/H <sub>2</sub> O <sub>2</sub>	\$2.2	\$0.3	BAC	\$7.4	\$0.6				
	—	—	UV	\$2.2	\$0.3				
Total	\$36.4	\$5.1	Total	\$26.4	\$2.8				
Savings	—	—	Savings	\$10.0	\$2.3				

Based on data from Snyder et al. (2014) and Gerrity et al. (2014)

## Ozone Contactors



## BAC Columns



## FUTURE WORK

- Evaluation of biological activity in the BAC columns based on adenosine triphosphate (ATP) and TOC removal
- Investigation of O<sub>3</sub>/TOC ratios of 0.0, 0.25, 0.50, 1.00, and 1.50 based on bulk organic matter transformation and TOC oxidation
- Evaluation of EBCTs of 0, 5, 10, 15, and 30 minutes based on TOC and TOC removal
- Evaluation of proprietary absorbance in addition to BAC
- Characterization of UV absorbance and fluorescence using a Horiba Analytical spectrofluorometer to assess bulk organic matter transformation during ozonation and removal through BAC
- Optimization of ozone-BAC with regards to the 0.5 ppm CDPH threshold for potable reuse water
- Quantification of total and fecal coliforms using the Colilert method and QuantiTray 2000 quantification protocol

## REFERENCES

1. Gerrity, D., Gamage, S., Holdy, J.C., Mahoney, D.B., Quinones, O., Trethowan, A., and Snyder, S.A. (2013) Pilot-scale evaluation of ozone and biological activated carbon for the removal of contaminant mitigation and disinfection. Water Research 45, 2155-2165.
2. Gerrity, D., Owens-Bennett, E., Venezia, T., Stanfield, B.D., Plumlee, M.H., DeBroux, J., Truesell, R.S. (2014) Applicability of ozone and biological activated carbon for potable reuse. Ozone Sci. Eng., in press.
3. Reungoat, J., Escher, B.I., Macova, M., Argaud, F.X., Gernjak, J.K., and Keller, J. (2012) Ozonation and biological activated carbon filtration of wastewater treatment plant effluents. Water Research 46, 863-872.
4. Reungoat, J., Macova, M., Escher, B.I., Caswell, S., Mueller, J.F., and Keller, J. (2010) Removal of micropollutants and reduction of biological activity in a full-scale ozonation plant for effluent treatment. Water Research 44, 6258-627.
5. Snyder, S.A., van Guntion, U., Arny, G. and DeBroux, J. (2014) Use of ozone in water reclamation for contaminant oxidation. WRF-08-05, WaterReuse Research Foundation.

## ACKNOWLEDGEMENTS

I would like to thank Dr. Daniel Gerrity for providing me with the opportunity to pursue this research. I would also like to thank the City of Las Vegas for providing me with the space to perform the research. The BAC was provided by the Upper Occoquan Service Authority through their support of WaterReuse Research Foundation Project 11-02. Finally, I would like to thank the Nevada Water Resources Research Institute (NWRI) for providing the primary funding source for this research.

# Estimation of Atmospheric Wet and Dry Deposition of Nutrients to Lake Tahoe Snowpack

## Basic Information

<b>Title:</b>	Estimation of Atmospheric Wet and Dry Deposition of Nutrients to Lake Tahoe Snowpack
<b>Project Number:</b>	2013NV195B
<b>Start Date:</b>	3/1/2013
<b>End Date:</b>	12/31/2014
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV002
<b>Research Category:</b>	Water Quality
<b>Focus Category:</b>	Nutrients, Hydrology, Water Quality
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Rina Schumer

## Publications

1. Obrist, D., Moore, C. W., Pearson, C., Pierce, A. M., Schumer, R., Helmig, D., Van Dam, B., Fain, X., Steffen, A., Staebler, R., Nghiem, S., Douglas, T., 2013: Mercury in alpine and Arctic snow: atmospheric deposition and fate processes, Seminar, Graduate Program of Hydrologic Sciences, University of Nevada: Reno, NV, April 1, 2013
2. Pearson, C., Obrist, D., Schumer, R., 2013: Nutrient and Mercury Concentrations and Loads in Tahoe Basin Snowpack, AGU Fall Meeting: San Francisco, CA, December 9, 2013
3. Pearson, C., Obrist, D., Schumer, R., 2013: Nitrogen and Phosphorus Concentrations and Loads within Lake Tahoe Snowpack, University Council on Water Resources 2013 Annual Conference: Lake Tahoe, CA, June 1, 2013, Published
4. Obrist, D., Moore, C. W., Douglas, T. A., Steffen, A., Staebler, R. M., Pearson, C., 2012: Concentrations of total and dissolved Hg in snow and vapor deposition collected during Atmospheric Mercury Depletion Events (AMDEs) in Barrow, Alaska during the BROMEX campaign. Abstract A31D-0059, AGU Fall Meeting: San Francisco, CA
5. Pearson, C., Obrist, D., Schumer, R., 2012: Quantifying Nutrient and Mercury Concentrations and Loads in Tahoe Snowpack, Water Summit 2012: Milwaukee, WI.
6. Pearson, C., Obrist, D., Schumer, R., 2012: Quantifying Nutrient and Mercury Concentrations and Loads in Lake Tahoe Snowpack, Abstract B23H-0540, Presentation at AGU 2012 Fall Meeting: San Francisco, CA, December 3, 2012.



**NIWR Project 2013NV195B**  
**Estimation of Atmospheric Wet and Dry Deposition of Nutrients**  
**to Lake Tahoe Snowpack**

**Problem and Research Objectives**

This study aims to fill gaps in nitrogen, phosphorous, and mercury deposition loads contained in snowfall and snowpack throughout the Tahoe basin using experimental measurements and spatial modeling. Developing atmospheric deposition constraints is needed to understand mobility and transport pathways of N and P from the watersheds to the lake, which account for a significant fraction of nutrient inputs to the lake. Comprehensive management practices to reduce N and P loads to Lake Tahoe will benefit from improved estimates of nutrient deposition to terrestrial basin areas, particularly since these provide a long-term source for potential N and P inputs to Lake Tahoe. Measurement and modelling of mercury deposition was added to this project in an effort to extend expertise in Mercury cycling in high alpine watersheds.

We will fill the gap in Tahoe Basin terrestrial atmospheric deposition estimates using an integrated approach that includes experimental measurements of wet deposition loads and snowpack accumulation in the Lake Tahoe watershed, combined with spatial modeling to extrapolate snowpack loads of N, P, and Hg to the entire watershed area. The role of snowpack deposition of nutrients is considered key in the Lake Tahoe basin given that seventy percent of annual precipitation occurs during winter and spring as snow and results from a National Atmospheric Deposition Program (NADP) stations in Sagehen Creek indicating that up to two-thirds of annual wet deposition of nutrients is associated with winter and spring snowfall.

**Methods**

Wet deposition loads in the basin are measured using both wet deposition samplers and snowpack core sampling. A number of wet deposition samplers are deployed in the Lake Tahoe watershed to continuously collect wet deposition samples, one located at a high elevation, remote site on top of Homewood ski area and a second location in Incline Village, NV. Since the Lake Tahoe Basin straddles the boundary of Nevada and California, field work will occur in both states. Wet deposition samples are collected every two weeks. Along with bi-weekly wet deposition samples, snowpack core samples will be collected at seven sites in the basin, starting with the first measureable snowpack accumulation until spring melting has ended. These sites are distributed across elevations and along eastern and western transects, with three sites located in the western part of the watershed in California and four sites in Nevada

Basin-wide loads and distribution are assessed using chemical concentrations and loads measured throughout the snow seasons as well as basin-wide mean peak SWE estimates from SWE reconstruction for the Sierra Nevada from 2000 to 2011. Sierra SWE reconstruction employs accurate estimates of snow depletion rates based on MODIS Snow Covered Area and Grain size (MODSCAG) in order to estimate peak SWE. MODSCAG calculates fractional snow cover area and grain size from Moderate Resolution Imaging Spectroradiometer (MODIS) data.

## **Principal findings and significance**

Comparison of event-based snowfall and integrated snowpack concentrations indicated that dry deposition was a substantial source of TP, TAN, and particulate Hg deposition, while wet deposition was the primary pathway for NO<sub>3</sub><sup>-</sup>, DHg, and SO<sub>4</sub><sup>2-</sup> loading. Second, spatial and temporal pattern analysis suggested that out-of-basin sources were important for Hg, TAN, and NO<sub>3</sub><sup>-</sup> deposition, while in-basin sources controlled P deposition, with particularly high concentrations near urban areas, exceeding remote location concentrations by up to a factor of six. Third, Increased NH<sub>3</sub> emissions from the San Joaquin Valley and increased atmospheric vertical mixing during the onset of spring likely led to large increases of snowpack TAN during March and April. Fourth, chemical speciation showed that organic N concentrations in Tahoe snowpack were on average 50 percent of total N and a shift from about equal parts of DHg and particulate Hg in fresh snowfall toward mostly particulate-dominated Hg forms in the snowpack. Fifth, we observed losses of NO<sub>3</sub><sup>-</sup> during snowpack storage coinciding with losses of SO<sub>4</sub><sup>2-</sup> due to preferential elution during mid-season melt events and losses of DHg during storage which we attribute to photochemical reduction and re-emission.

Tahoe Basin snowpack is a substantial reservoir in which atmospheric nutrients and pollutants accumulated throughout winter and spring. Estimates of basin-wide annual snowpack mass loading showed accumulation of N, P, and Hg yielding 113 t of N, 9.3 t of P, and 1166.2 g of Hg. Through melt and runoff processes, nutrients and pollutants stored in snowpack will enter underlying terrestrial ecosystems and potentially be transported to streams and lakes (Oberts, 1994). While, much of the snowpack chemical pool will be immobilized by soil and plant uptake during melt, these inputs contribute to a large terrestrial pool that may be mobilized at some future point in time. Further research should focus on quantifying the relationship between snowmelt processes and stream and groundwater input. One particularly interesting aspect to address is the substantial amount of organic N stored within the basin's snowpack each year and its relatively unknown sources or role in high elevation nutrient cycling of the Sierra Nevada.

## **Information Transfer Activities**

### **Presentations**

Obrist, D., Moore, C. W., Pearson, C., Pierce, A. M., Schumer, R., Helmig, D., Van Dam, B., Fain, X., Steffen, A., Staebler, R., Nghiem, S., Douglas, T., 2013: Mercury in alpine and Arctic snow: atmospheric deposition and fate processes, Seminar, Graduate Program of Hydrologic Sciences, University of Nevada: Reno, NV, April 1, 2013

Pearson, C., Obrist, D., Schumer, R., 2013: Nutrient and Mercury Concentrations and Loads in Tahoe Basin Snowpack, AGU Fall Meeting: San Francisco, CA, December 9, 2013

Pearson, C., Obrist, D., Schumer, R., 2013: Nitrogen and Phosphorus Concentrations and Loads within Lake Tahoe Snowpack, University Council on Water Resources 2013 Annual Conference: Lake Tahoe, CA, June 1, 2013, Published

Obrist, D., Moore, C. W., Douglas, T. A., Steffen, A., Staebler, R. M., Pearson, C., 2012: Concentrations of total and dissolved Hg in snow and vapor deposition collected during Atmospheric Mercury Depletion Events (AMDEs) in Barrow, Alaska during the BROMEX campaign. Abstract A31D-0059, AGU Fall Meeting: San Francisco, CA

Pearson, C., Obrist, D., Schumer, R., 2012: Quantifying Nutrient and Mercury Concentrations and Loads in Tahoe Snowpack, Water Summit 2012: Milwaukee, WI.

Pearson, C., Obrist, D., Schumer, R., 2012: Quantifying Nutrient and Mercury Concentrations and Loads in Lake Tahoe Snowpack, Abstract B23H-0540, Presentation at AGU 2012 Fall Meeting: San Francisco, CA, December 3, 2012,

### **Publications**

Christopher C. Pearson, Rina Schumer, Daniel Obrist, Dale Johnson, Karl Rittger (in review). Nutrient and mercury deposition and storage in an alpine snowpack, Sierra Nevada Mountains, USA. Submitted to *Biogeosciences*.

### **Student Support**

This project supported the Master's work for Chris Pearson, who graduated in December 2013. Chris produced numerous conference presentations (above) and has a manuscript submitted to *Biogeosciences*. A new Master's student, Benjamin Trustman is currently funded by this project.

# Quantifying Surface Runoff and Water Infiltration in Arid and Semi-arid Areas

## Basic Information

<b>Title:</b>	Quantifying Surface Runoff and Water Infiltration in Arid and Semi-arid Areas
<b>Project Number:</b>	2013NV196B
<b>Start Date:</b>	3/1/2013
<b>End Date:</b>	2/28/2015
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV01
<b>Research Category:</b>	Climate and Hydrologic Processes
<b>Focus Category:</b>	Surface Water, Models, Water Quantity
<b>Descriptors:</b>	
<b>Principal Investigators:</b>	Yong Zhang, Li Chen, Donald M Reeves

## Publications

1. Zhang, Y., L. Chen, D. M. Reeves, and H.G. Sun, Fractional-derivative models for surface runoff along heterogeneous ground surface. Abstract will be published in the 2014 International Conference on Fractional Differentiation and its Applications, Catania, 23-25 June, 2014.
2. Sun, H.G., M. M. Meerschaert, Y. Zhang, J.T. Zhu, and W. Chen, A fractal Richards' equation to capture the non-Boltzmann scaling of water transport in unsaturated media, *Advances in Water Resources*, 52, 292-295, 2013.
3. Sun, H.G., Y. Zhang, W. Chen, and D. M. Reeves, Use of a variable-index fractional-derivative model to capture transient dispersion in heterogeneous media, *Journal of Contaminant Hydrology*, 157, 47-58, 2014.

## **NIWR Project 2013NV196B**

### **Quantifying Surface Runoff and Water Infiltration in Arid and Semi-arid Areas**

#### Problem and Research Objectives

Water resources are critical to sustainable development in arid and semi-arid areas. The processes of surface runoff and infiltration govern the fate of precipitation reaching the land surface, and thus control the total amount and timing of precipitation available to generate streamflow and replenish aquifers. This project proposes the use of novel mathematical models to quantify the complex dynamics of surface runoff and infiltration in order to protect water resources and the environment in Nevada.

#### Methodology

In this study, we applied state-of-the-art physical theories and novel mathematical tools to build and solve the physical models for surface runoff process. Random walk theories combined with the subordination technique can account for the nonlocal movement of water packages along a ground surface exhibiting fractal complexity. The local variation of flow behavior can also be captured by conditioning on local soil and topography properties. The resultant model explains the scale evolution of surface runoff within and across sub-basins through the use of the new mathematical concept of tempered stable laws.

We also generalized the Richards' equation using the physical concept of fractal time, which accounts for both the sub-diffusive and super-diffusive anomalous motion of moisture observed in heterogeneous, unsaturated soils.

#### Principal Findings and Significance

We developed novel stochastic theories and mathematical models to quantify the complex dynamics of surface runoff along regional-scale land surface with multi-scale heterogeneity, and water infiltration in real-world unsaturated soils. We show:

1. The real-world infiltration process can be efficiently captured by a fractal Richards' equation (FRE). The traditional Richards' equation implies that the wetting front in unsaturated soil follows Boltzmann scaling, with travel distance growing as the square root of time. In laboratory experiments and field measurements, the evolution of a horizontal wetting front can deviate significantly from Boltzmann scaling. To capture the non-Boltzmann scaling of water transport in unsaturated soils, we propose a fractal Richards' equation, replacing the integer-order time derivative of water content by a fractal derivative, using a power law ruler in time.
2. The FRE solutions can be obtained either semi-analytically or numerically (using a finite difference solver), which exhibit anomalous non-Boltzmann scaling. Applications show that the FRE fits well water content curves from various previous literature. This work was published in Sun et al. [2013].
3. The multi-scale heterogeneity nature of soils, especially the soil fractal dimension, may result in a full range of anomalous dynamics in water infiltration. This includes the sub-diffusive regime, when regions of flow permeability can retard flow, and super-diffusion, where the wetting front is accelerated along preferential flow paths.

4. We find that the fractal time index in the FRE model may be related to soil texture parameters, especially the fractal dimension. This work was published in Sun et al. [2013].
5. Surface runoff and water infiltration in arid and semi-arid areas may not exhibit constant scaling, and may instead transition between diffusive states (i.e., super-diffusion, sub-diffusion, and Fickian diffusion) at various transport scales. These transitions are likely attributed to physical properties of the medium, such as spatial variations in medium heterogeneity (i.e., soil hydraulic properties and topography). We refer to this transitory dispersive behavior as “transient dispersion”.
6. We propose a variable-index fractional-derivative law (FDL) to describe the underlying transport dynamics for “transient dispersion”. The new theory generalizes the standard constant-index FDL which is limited to stationary heterogeneous media. Numerical methods including an implicit Eulerian method and a Lagrangian solver are utilized to produce variable-index FDL model solutions. Applications show that the variable-index theory can efficiently quantify the observed scale transitions, with the scale index varying linearly in time or space. This work was published in Sun et al. [2014].
7. Hydrological response to precipitation in real-world watersheds and sub-basins exhibits non-Fickian behavior. Surface runoff along regional-scale land surface can be either continuous or discontinuous, forming complex patterns of overland flow. The resultant hydrograph therefore contains either early arrivals or delayed arrivals, or even the mixture of both arrivals. This work will be presented by Zhang [Zhang et al., 2014, submitted].

#### Information Transfer Activities

##### Papers:

- Zhang, Y., L. Chen, D. M. Reeves, and H. G. Sun, A fractional-order tempered-stable continuity model to capture surface water runoff, *Journal of Vibration and Control*, Submitted, 2014.
- Sun, H.G., M. M. Meerschaert, Y. Zhang, J.T. Zhu, and W. Chen, A fractal Richards’ equation to capture the non-Boltzmann scaling of water transport in unsaturated media, *Advances in Water Resources*, 52, 292-295, 2013.
- Sun, H.G., Y. Zhang, W. Chen, and D. M. Reeves, Use of a variable-index fractional-derivative model to capture transient dispersion in heterogeneous media, *Journal of Contaminant Hydrology*, 157, 47-58, 2014.

##### Presentation:

- Zhang, Y., L. Chen, D. M. Reeves, and H.G. Sun, Fractional-derivative models for surface runoff along heterogeneous ground surface. Abstract (accepted already) will be published in the 2014 International Conference on Fractional Differentiation and its Applications, Catania, 23-25 June, 2014.

#### Student Support

A majority of this grant will be used to support a graduate student. Due to the budget cut in the first year, we could not hire any student. However, we saved the budget and we will use it to fund one graduate student in the 2nd year. This student will help with physical model development and applications.

# Impact of climate on mercury transport in the Carson River-Lahontan Reservoir system and Management Alternatives to Mitigate Response

## Basic Information

<b>Title:</b>	Impact of climate on mercury transport in the Carson River-Lahontan Reservoir system and Management Alternatives to Mitigate Response
<b>Project Number:</b>	2013NV197B
<b>Start Date:</b>	3/1/2013
<b>End Date:</b>	2/28/2015
<b>Funding Source:</b>	104B
<b>Congressional District:</b>	NV002
<b>Research Category:</b>	Not Applicable
<b>Focus Category:</b>	Non Point Pollution, Surface Water, Models
<b>Descriptors:</b>	None
<b>Principal Investigators:</b>	Rosemary Woods-Hart Carroll

## Publications

There are no publications.

**NIWR Project 2013NV197B**  
**Impact of Climate on Mercury Transport in the Carson River-Lahontan Reservoir System**  
**and Management Alternatives to Mitigate Response**

Problem and Research Objectives

The rate of Hg transported through the CRLR system and the resulting bioaccumulation in the reservoir is non-linearly related to in-stream flow (Carroll, 2010). It is therefore vitally important to relate changes to in-stream flow regimes caused by climate change with the fate of Hg in this important freshwater system.

Studies (IPCC, 2007; USGCRP, 2009) suggest that the future envelopes of climate variability may differ from historical data, with all regions in the southwestern US predicted to have increased temperatures and most regions predicted to experience a change in precipitation. The US Bureau of Reclamation (USBR, 2011) developed hydrologic responses associated with 112 down-scaled climate projections from the World Climate Research Programme Coupled Model Intercomparison Project 3. Hydrologic projections are based on the Variable Infiltration Capacity (VIC) macroscale hydrology model. The projected flows at Fort Churchill on the Carson River show that while uncertainty in projected flows increases significantly by 2070s, there is also significant increase in the median seasonal flow volume in the winter and a decrease in flows during the spring-summer runoff period. This change in precipitation will lead to changes in stream flow, which could affect the Hg transport in the CRLR system.

This project aims to establish the impact of projected climate on Hg transport through the CRLR system and the significance of change in terms of timing and total mass of each Hg species modeled (total Hg, total dissolved Hg, total methylmercury (MeHg) and total dissolved MeHg). Using the results for the MeHg, the impacts of projected climate on MeHg bioaccumulation in Lahontan Reservoir will be determined. From there, management alternatives to reduce Hg transport and/or bioaccumulation into the reservoir as functions of changing climate will be developed and tested.

Methodology

Methods described pertain to only those completed during year 1 of the project. Future work addresses anticipated methods for 2014. Primarily, work to date has developed boundary conditions for the CRLR Hg transport model based on VIC predicted flows.

1. Observed flows at the Woodfords gage (10310000) on West Carson, Gardnerville gage (10309000) on the East Carson were correlated to predict historic flows at the Carson City Gage (gage number 10311000) on the main Carson River, from 1990 to present. This transfer is necessary since the CRLR Hg transport model uses the Carson City gage as its upstream flow boundary, not the Woodsville or Gardnerville gages predicted by VIC. Data were separated by month and log-log regressions were performed to correlate the data. September and October were split in half to improve correlation and was likely required based on late season irrigation practices.
2. The bias correction process from “West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections” was followed to reduce the existing bias between the observed and VIC predicted flows in the historical period. To do this, an empirical cumulative distribution function (ECDF) was found for both the observed and the projected data from 1950-1999. The VIC predicted output was then transformed by finding the percentile of the flow according to the ECDF of the projected



data, and then using that percentile to find the corresponding flow in the ECDF of the observed data, which was used as the bias corrected flow and performed for Woodfords, Gardnerville and Fort Churchill Gages (10312000). Error in VIC bias-corrected flows reduced error (nrmse) from greater than 14% at all gage locations to 3.4% at Woodfords, 3.6% at Gardnerville and 4.1% at Fort Churchill for the historic record 1950-1999.

3. Bias correction factors calibrated for the historic record were applied to future VIC predictions for years 2000 to 2099. Future Woodsville and Gardnerville flows were then translated into Carson City Gage flows based on regression statistics described in (1). Carson City gage and Fort Churchill gage daily flows were used to develop RIVMOD input.
4. The Hg transport model requires the stage of the Lahontan Reservoir and the discharge from the Lahontan Dam as inputs. A spreadsheet model was created to model these parameters from the available data. The inputs to the spreadsheet are the average monthly flow from the Fort Churchill gage, representing the input from the Carson River, and the Truckee Canal (which enters the Lahontan Reservoir near the dam on the northern end of the reservoir). The initial storage, found from USGS gage data (10312100), is also set. Stage is then tracked as a function of inputs as well as the required release due to agricultural demands downstream and maximum reservoir stage.
5. The calibrated reservoir model was run over future VIC scenarios from 2000 to 2099 using average monthly Truckee Canal inflows to establish future reservoir stages and discharged based on historic reservoir operations. Reservoir discharge and stage, along with Truckee Canal inflows were input to RIVMOD at the daily stress period for future WASP/RIVMOD simulations.
6. CRLR model files are currently being placed on the DHS computer Cluster in 112 separate directories and compiled. While WASP input files will remain identical between individual climate scenarios, RIVMOD input files will contain flows and stages related to each of the VIC 100-year scenarios spanning 2000-2099. Model execution is slated to begin at the end of May 2014 and will continue for 3-6 months.

### Principal Findings and Significance

Significant findings with respect to Hg transport and bioaccumulation will occur in year 2 of this project. Principal findings related to boundary conditions are provided below.

1. Correlation between Woodfords and Gardnerville gages to Error in analysis found a normalized root mean squared error (nrmse) less than 2%. Error in flow correction was larger when divided into specific flow regimes based on Hg transport mechanism. Specifically, diffusion dominated flow (< 106 cfs) had a nrmse equal to 25%; turbulent mixing flow (106-354 cfs) had a nrmse equal to 33%; flows responsible for bank erosion (354-3900 cfs) had a nrmse equal to 16% while overbank flows (> 3900 cfs) had a nrmse equal to 30%.
2. Unbiased VIC predicted flows at Woodfords, Gardnerville and Fort Churchill gages had nrmse in excess of 14% when comparing to observed historic flows 1950-1999. The bias corrected daily projections are greatly improved by reducing error to 3.6%, 3.4% and 4.1%, respectively.
3. An illustration of future flows at the Fort Churchill gage compared to historic (i.e. observed) flows for six VIC realizations are provided in Figure 1. Included in Figure 1 is the average of historic and future monthly flows for all 112 VIC realizations. In general,

future flows increase over historic flows during October through March and are lower than historic flows. Peak discharge is estimated to still occur in May, but with 20% less volume while summer flows are significantly reduced. Implications on Hg transport and bioaccumulation will be evaluated in year 2.

4. No relationship was found between the Truckee Canal inflows to Lahontan Reservoir and observed Fort Churchill flows, reservoir storage or reservoir release. For these reasons average monthly Truckee Canal inflows were used in the future projections of reservoir stage and release.
5. The spreadsheet model has a tendency to over predict peak reservoir stage and under predict minimum reservoir stage. Error in stage and reservoir release is approximately 13% and 17%, respectively. However, modeled reservoir operations captures observed reservoir response to wet and dry years and is felt sufficient to move forward with Hg transport simulations.

#### Information Transfer Activities

All proposed information transfer activities are slated for year 2.

#### Student Support

Allison Flickenger is supported at the Masters level within the Graduate Program of Hydrologic Sciences at the University of Nevada, Reno.

#### Future Work (Year 2)

Future work will include the following:

1. Execute WASP/RIVMOD on the DHS cluster. Each run will require approximately 3 months to run to completion. Given the cluster contains 99 nodes, full completion of all 112 climate runs will require the simulation to continue into and through the fall months.
2. Allison will use the time the model is running on the cluster to (a) write and present her proposal (b) check model output to ensure model execution is preceding appropriately and (c) learn the Bioaccumulation and Mercury Mass Balance model (BMMBM) developed for Lahontan Reservoir.
3. Analysis of Hg output to assess possible shifts in Hg transport caused by hydrologic shifts and uncertainty associated with this shift. Analysis will be done spatially through the river and reservoir at the decadal temporal scale.
4. The bioaccumulation and mercury mass balance model will be run with DMeHg output with bioaccumulation compared at the decadal temporal scale.
5. Develop management alternatives to see if bioaccumulation can be mitigated in the face of climate change.
6. Code WASP/RIVMOD and run these management scenarios on those VIC runs responsible for greatest shift in transport and bioaccumulation.
7. Write and present MS thesis to the committee.
8. Present at NWRA, winter 2015
9. Submit a paper to a peer reviewed journal.

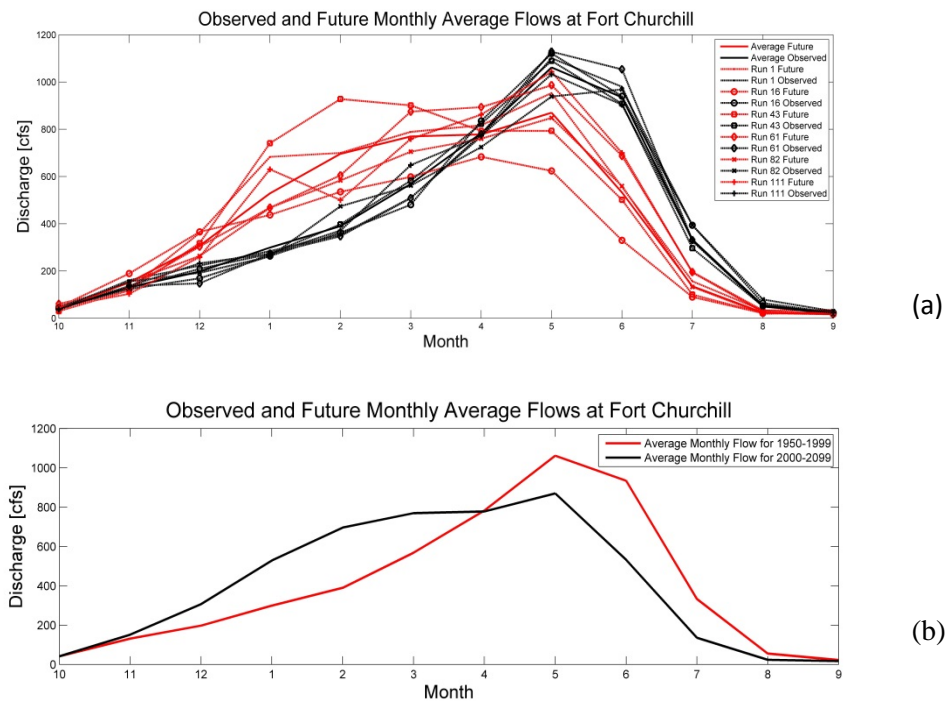


Figure 1: A comparison of average monthly historic flows and future VIC flows at the Fort Churchill gage on the Carson River, NV.

### References Cited

- Carroll, R.W.H. 2010. Modeling mercury transport and bioaccumulation in the Carson River and Lahontan Reservoir System, Nevada. Dissertation. University of Nevada, Reno. 170 pp.
- Intergovernmental Panel on Climate Change (IPCC). 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H.L. Miller (eds.). Cambridge University Press, Cambridge, United Kingdom and New York, New York, United States, 996 pp. Available at <http://www.ipcc.ch/ipccreports/ar4-wg1.htm>.
- United States Bureau of Reclamation (USBR). 2011. West-wide climate risk assessments: bias-corrected and spatially downscaled surface water projections. Technical Memorandum no. 86-68210-2011-01. 138 pp.
- United States. Global Change Research Program (USGCRP). 2009. Global Climate Change Impacts in the United States, T.R. Karl, J.M. Melillo, and T.C. Peterson, (eds.). Cambridge University Press, 196 pp.

# **Information Transfer Program Introduction**

None.

# **USGS Summer Intern Program**

None.

<b>Student Support</b>					
<b>Category</b>	<b>Section 104 Base Grant</b>	<b>Section 104 NCGP Award</b>	<b>NIWR-USGS Internship</b>	<b>Supplemental Awards</b>	<b>Total</b>
<b>Undergraduate</b>	1	0	0	0	1
<b>Masters</b>	4	0	0	0	4
<b>Ph.D.</b>	3	0	0	0	3
<b>Post-Doc.</b>	1	0	0	0	1
<b>Total</b>	9	0	0	0	9

## **Notable Awards and Achievements**

The project titled "Optimization of Ozone-Biological Activated Carbon Treatment for Potable Reuse Applications" largely funded the research endeavors (time, instruments and travel) during completion of Ashley Selvy's M.S.E. degree. Ashley is expected to graduate in May 2015. Ashley presented a poster at the Nevada Water Resources Association 2014 Annual Conference and was awarded 2nd Place in the student poster competition.